UNIVERSITY OF CALIFORNIA PUBLICATIONS
IN
AGRICULTURAL SCIENCES

Vol. 4, No. 11, pp. 339-396, 21 figures in text June 30, 1922

STUDIES ON A DRAINED MARSH SOIL UNPRODUCTIVE FOR PEAS

BY
PAUL S. BURGESS

CONTENTS

INTRODUCTION

The unparalleled progress made during recent years in chemistry and physics has given decided impetus to the development of scientific methods in soil science and in the science of plant physiology, which are rapidly supplanting the older, more empirical methods of experimentation.[28*] New and improved procedures are constantly appearing for the elucidation of problems involving a lack of soil fertility, while the fundamental questions of plant nutrition are being investigated with thoroughness and the results interpreted with discriminating care.

* Literature cited, pp. 393 to 396.

At present, the more important factors recognized as bringing about a state of infertility in soils are:

1. Untoward climatic conditions.

2. Too slight a concentration, at some time during the growth period, of one or more essential mineral elements dissolved in the soil solution, or the lack in the solution of a proper physiological balance of ions or salts.

3. The presence of substances dissolved in the soil solution which may be toxic to plant growth; these may be either of organic or inorganic nature.

4. Poor physical conditions obtaining in either the surface or the subsoil.

5. A condition of either abnormal or subnormal activity on the part of certain of the soil's micro-organic population.

6. The absence of sufficient quantities of organic materials undergoing active decomposition.

Until comparatively recently, agricultural chemists and students of plant nutrition have accepted the earlier and more obvious explanations of most of these facts without question, while the newer conceptions went unproved and unchallenged. Now, however, studies of cell permeability are being made, the questions of antagonism between ions, and of proper physiological balance between salts in both soils and solution cultures are being considered, while explanations of such observations are being advanced. The rapidity with which a soil is able to replenish or renew solutes absorbed from its solution, as well as the total concentration at any given time during the growth period, is now recognized as of extreme importance to continued crop production. The use of the conductivity apparatus and the cryoscopic method has given much valuable comparative data along these lines, and has opened fields heretofore unexplored, while delicate quantitative methods have also been perfected in this connection. Great advances have recently been made in the study of the nature of soil acidity as well as in methods for its accurate determination. And finally, the recent investigations in the realm of soil colloids—the effects upon the colloids of salt applications, as well as the direct effects of the colloids themselves in regulating the concentration of the soil's solution, and in modifying its moisture relations—should receive merited attention.

Armed with this knowledge, the soil scientist is today better able than ever to cope with the many obscure and puzzling problems of

low productivity in soils, which, although everywhere encountered, are especially apparent in the more arid or semi-arid sections of this country. The application of these modern methods to the solution of practical field problems now demands our attention if their benefits are to be of direct value to the practice of agriculture. To this end, the experiments herein described were undertaken.

Statement of the Problem

Large areas of tidewater and overflow lands bordering the San Pablo and San Francisco bays and the Sacramento and San Joaquin rivers have in the past been drained and are at present used to grow a variety of crops. Certain areas within these reclaimed sections, varying in extent from an acre to many hundreds of acres, are unproductive for certain crops. The study discussed in this paper deals with a careful investigation of one partially unproductive area comprising about a thousand acres, located at Ignacio, California, on the property of the California Packing Corporation. The owners of this ranch were especially desirous of growing peas for canning purposes on the land under experiment, but have had very poor crops during the past few years. The peas ordinarily sprout and come up well, but when five or six inches high, turn yellow and gradually die. A few plants of each crop always mature, but hardly a third of a normal crop usually is harvested. When we consider that there are thousands of acres of similar lands in California which have been drained and brought under cultivation at great expense, the importance of a careful and thorough study of this problem can hardly be overemphasized.

METHODS EMPLOYED

As has been stated, one of the main objects of the present investigation was to test the applicability of certain modern methods of soil research to the solution of a practical field problem. Among those methods which have recently come into considerable prominence may be cited the periodical-water-extraction procedure, which has been largely developed and standardized by the work of Burd,[5] Hoagland,[21] and Stewart.[44] The water extraction idea for soil investigations is not a new one. It has been used in Europe for over sixty years,* and

* An extensive bibliography is given by Stewart.[44]

twenty years ago in this country, King[25, 26] applied it to comparative fertility work in the field. Also, in the method proposed by Burd and his associates the extraction procedure and certain other details are quite similar to those used by our Federal Bureau of Soils many years ago. The difference between the two lies in the manner of application to the problem, and in the method of interpreting the results. One of the chief points of weakness attaching to the procedures of the earlier workers, and never satisfactorily overcome by them, has now been surmounted through the careful and painstaking work of Stewart,[44] Hibbard,[19, 20] and others. I refer to methods of chemical analysis of the soil extract. In the earlier work, analytical methods were usually far too crude to differentiate between the slight differences often obtaining. Inaccurate colorimetric methods were then the rule. Today, these have largely been supplanted by volumetric and gravimetric procedures which insure more accurate results. The general method of experimentation mentioned above is given in detail by Stewart.[44]

During the past few years several field tests with fertilizers have been made upon the soil under study. The application of lime has occasionally increased yields somewhat, and the addition of superphosphate has consistently improved conditions, although the cost of the applications has not always been met. A preliminary examination made by the writer showed the soil to be very acid in reaction, while the deeper layers of the subsoil carried large quantities of the "white alkali" salts, notably sulfates.

With the results and methods just discussed in mind, it was decided to conduct two series of experiments: first, a set of plot tests in the field, applying superphosphate to certain plots and liming others to neutrality, proper checks being maintained; and, second, a pot experiment with various soil amendments, to be carried out in the greenhouse on the campus of the University of California; the same soil to be used and peas to be grown in both cases. The two crops were to be planted at the same time, and soil samples were to be drawn periodically from each, extracted and analyzed. Soil reaction under the growing crops was also to be closely followed, while alkali determinations were to be made from time to time in the field soil. The presence or absence of soluble organic soil toxins could also be noted by the application of an excess of $CaCO_3$, for Truog and Sykora[45] have shown such poisonous constituents to be rendered innocuous in soils by the complete neutralization of soil acidity as well as by the use of certain other soil amendments.

Both the field and the pot soils were sampled every four weeks during the growing period except as noted below. A sample was drawn from directly beneath the row of growing plants, from four places in each plot (see fig. 1), care being taken to obtain a representative sample down to a depth of 7 inches (surface soil). The twelve individual samples from the checks and a like number from the phosphate plots were then mixed very thoroughly and quartered down for the final composite samples. These were brought at once to the laboratory, passed through a 2 mm. sieve, and placed in tight Mason

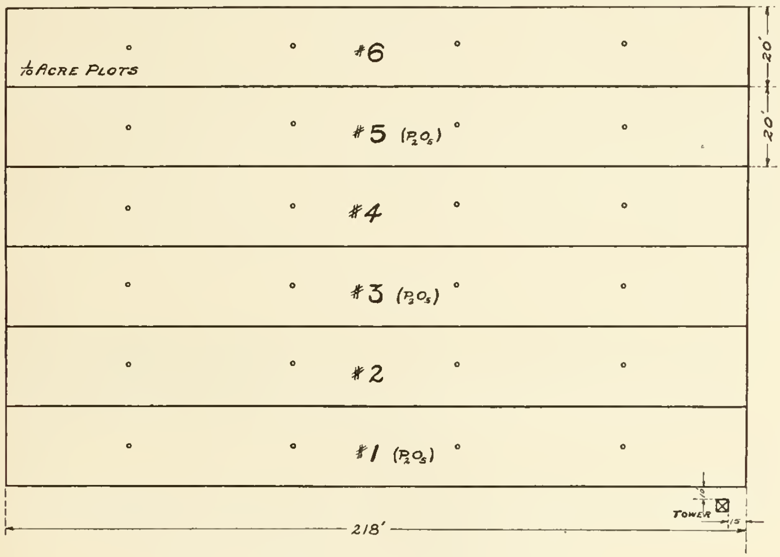

Fig. 1.—Method of sampling plot soils.

jars, after withdrawing sufficient soil for moisture determinations. The proper amounts of the moist soils, the percentages of moisture being taken into consideration, were then weighed out to make 300 g. of water-free soil, to which sufficient distilled water was added to bring the proportion of water to soil up to exactly 5 to 1. The mixtures of soil and water were now shaken for one hour in an end-over-end shaking machine, running at a speed of 7 revolutions per minute. Settling was allowed to take place overnight, after which the supernatant liquids were siphoned off and filtered through Pasteur-Chamberland filters. The resulting clear solutions were used for analysis by methods which will be given later. Hydrogen-ion determinations were made upon portions of the moist soils as soon as received at the laboratory. The hydrogen electrode described by Sharp and Hoagland[42] was employed.

In the greenhouse pot experiment a sharp small-bore 18-inch cheese trier was used in sampling, each core being taken from the entire depth of soil. In order to obtain sufficient soil for the water extractions, it was necessary to take three cores from each pot at each sampling. The resulting holes were always filled with similar dry, untreated soil. Proper precautions were employed to avoid subsequent sampling in the same places. The moist soils were placed at once in tight Mason jars and hydrogen-ion determinations and extracts were subsequently made in exactly the same way as described for the

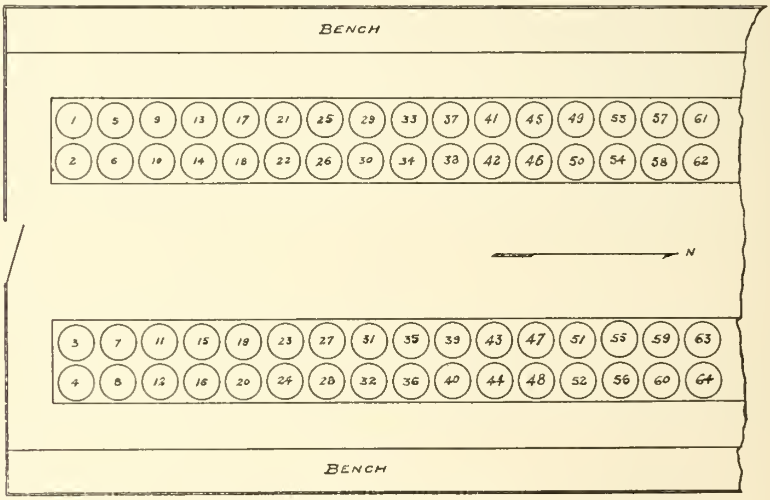

Fig. 2.—Arrangement of pots in greenhouse experiment.

field samples. Conductivity measurements were made upon the extracts at each sampling. The simple Kohlrausch conductivity outfit was employed. A detailed description of the apparatus, together with conversion tables, is given by Oswald and Luther[39] (pp. 461–477). The specific resistances (in ohms), rather than their reciprocals, the specific conductivities, have been employed in the work hereafter reported.

The clear soil extracts were regularly analyzed for the following ions, Ca, Mg, K, PO_4 and NO_3, supplemented by occasional determinations of SO_4, Cl, and Al. Carbonates and bicarbonates were usually absent except where lime was used. The PO_4-, Ca-, and K-ions were determined in accordance with the methods proposed by Stewart[44] (pp. 328, 329), except that 600 cc. aliquots were found necessary in the case of PO_4-ion, while 400 cc. portions were used for Ca and K.

Nitrates and chlorides were run by the phenoldisulphonic acid method and by titration with a standard silver nitrate solution, respectively. These methods are essentially those widely used in sanitary water analysis.[1] Magnesium was determined gravimetrically as the pyrophosphate in the filtrate from the calcium oxalate precipitate, after first evaporating to dryness and burning off ammonium salts. Sulfates were determined gravimetrically, weighing as $BaSO_4$. Six hundred cc. aliquots of the original soil extracts were first evaporated to dryness, burned off, and taken up in very dilute hydrochloric acid before precipitation with barium chloride. The water-soluble sodium, silica, and aluminum were occasionally determined. In all cases aliquots were taken large enough to make possible the use of standard gravimetric procedures.

At the beginning of the work many determinations were made upon identical extracts in order to check up the results as regards accuracy of duplication. As a rule, the larger the amounts of the various ions present, the more accurate would be the determinations. For instance, in the case of K, when that ion was present above 40 p. p. m. (as was usually the case), duplicate determinations invariably checked within less than 3 p. p. m. In other words, the percentage variation between duplicates was here under 8 per cent. Better checks than this were usually obtained with Ca, Mg, NO_3, and Cl, while with PO_4, duplicates might differ by 1 p. p. m. when present in quantities of less than 5 p. p. m. The very small amounts of phosphorus always present in these soil extracts made this element unusually difficult to determine accurately. Sulfates always checked well in duplicate determinations.

Stewart[44] (pp. 332, 333) has discussed very fully the form, or method, of recording final results, and until more is definitely known about the true soil solution, it seems best to the writer, also, to express all results as ''parts per million of dry soil.'' This procedure has been followed throughout.

THE FIELD EXPERIMENTS

The Soil Type

The soil at Ignacio has been formed by the deposition of clay and very fine silt brought down by the Sacramento River. It is a light drab clay loam underlain at a depth of six to seven inches by a very deep, almost impervious, clay subsoil of lighter color. Neither the

surface nor the subsoil contains gritty particles of any kind and when wetted, both are extremely smooth, plastic, and sticky. Aeration is thus always poor and deep root development impossible. The apparent specific gravity of the surface soil when air dried and heavily compacted is 0.970. An acre to a depth of 6 inches thus weighs about 1,320,000 pounds or 660 tons. Its light weight is due chiefly to the 13 per cent of organic matter which it contains. The total water holding capacity (Hilgard method) is 104% of the moisture-free soil. The optimum moisture holding capacity is thus not far from 50% while the hygroscopic coëfficient is 14%.

Chemically, the soil presents a number of very interesting features. An analysis made by the Hilgard method (digestion for 40 hours at 100° C. in HC1, sp. gr. 1.115) on a representative composite sample from the poor area under study appears in Table I. Only those elements important to a discussion of plant nutrition were determined. The table also gives the amounts, in parts per million, of the various ions (computed as the oxides for comparison) soluble in water, determined by the methods previously described.

TABLE I

Chemical Analysis of Ignacio Soil

(Reduced to water-free basis)

	Strong Acid Soluble Per Cent	Water-Soluble p. p. m.
Insoluble matter (SiO_2)	58.60	55
Potash (K_2O)	0.23	54
Soda (Na_2O)	....	286
Lime (CaO)	0.66	125
Magnesia (MgO)	1.34	75
Iron (Fe_2O_3)	21.15	none
Alumina (Al_2O_3)		24
Phosphoric Acid (P_2O_5)	0.25	4
Sulfuric Acid (SO_3)	0.62	400
Total nitrogen (N)	0.36	......
Nitrates (NO_3)	....	150
Chlorine (Cl)	....	100
Loss on ignition (volatile)	13.25	......

Manganese was practically absent, as were also carbonates and bicarbonates. Negative tests were noted for ferrous salts.

These results are inserted merely to show the general chemical composition and the relative solubilities of this soil. It is interesting to observe the reversed "lime-magnesia ratio" when total percentages of these compounds are compared with their water-soluble portions;

also that the phosphoric acid, although not low in total percentage, is but very slightly soluble in water. High amounts of available potassium as well as the presence of considerable quantities of water-soluble aluminum are also shown.

As this soil was at one time below the level of San Pablo Bay, it was thought desirable at the inception of the work to make a careful alkali survey of the area, especially of that portion of it where it was later planned to conduct the field experiment. Accordingly, about 40 samples of surface soil were taken. Several borings were also made to a depth of 5 feet, the 1-foot samples being segregated and quantitatively analyzed for water-soluble chlorides and sulfates. Carbonates were absent. Bicarbonates were present in traces only. Table II presents the data secured. The figures for the surface soil are averages of 40 analyses, all of which agreed fairly closely. The subsoil samples (except top foot) are averages of duplicate borings. The number of samples averaged appears in the table.

TABLE II

ALKALI DETERMINATIONS

	$NaCl$ Per Cent.*	Na_2SO_4 Per Cent.*
Surface, 6 to 7 inches (40 samples)	0.018	0.066
Sub-soil, 1st foot (20 samples)	.100	.180
Sub-soil, 2d foot (2 samples)	.150	Heavy test†
Sub-soil, 3d foot (2 samples)	.450	Heavy test
Sub-soil, 4th foot (2 samples)	.710	Heavy test
Sub-soil, 5th foot (2 samples)	.880	Heavy test

The percentages of alkali present in the surface soil, although considered small, may possibly approach toxic concentrations where limited moisture conditions prevail. The large quantities of soluble salts in the subsoil probably exert no direct effect, for plants are seldom able to root there below 12 inches on account of the impervious, compact condition of the soil. That alkali and subsequent leaching have in the past contributed to these untoward conditions is probable. The work of Sharp,[41] as well as that of Hager,[15] has shown that soils, especially heavy clays, once saturated with solutions of soluble salts, or inundated with sea water and later washed free, are almost invariably left in a very poor and impervious physical condition.

* Percentages figured to *dry soil basis.* The surface soil contained 6% water (air dry), while the subsoil carried an average of 34% water when received at the laboratory.

† The writer did not quantitatively determine the sulfates in these samples.

The next factor to receive attention was soil reaction. Peas were to be grown and, in the past, a neutral or slightly alkaline reaction has been advocated for this crop. The Ignacio soil was found to be extremely acid. The hydrogen-ion concentration, as determined on a large number of fresh field samples, gave an average exponential value of $P_H = 4.46$. A preliminary experiment to ascertain the approximate lime requirement was performed after the method of electrometric titration with a standard solution of $Ca(OH)_2$ as proposed by Sharp and Hoagland.[42] Considering an acre-six-inches of this soil to weigh 660 tons (see above), it was found that 4 tons of calcium carbonate were immediately required to neutralize the concentration of hydrogen-ion present.* An experiment was now set up using 100-gram portions of the field soil and thoroughly mixing each with different amounts of pure $CaCO_3$. Optimum moisture conditions were maintained. Table III shows the lime treatments, together with the P_H values as determined from time to time.

TABLE III

LIME REQUIREMENT OF FIELD SOIL

Number	Tons $CaCO_3$ per-Acre	Grams $CaCO_3$ per 100 Grams Soil	P_H After 1 week	P_H After 1 month	P_H After 5 months	P_H After 7 months
1	3	0.45	6.3	5.7	5.5	5.4
2	4	0.60	7.0	6.0	5.9	5.9
3	5	0.75	7.1	5.3	6.1	5.5
4	6	0.90	7.2	6.6	6.6	6.5
5	8	1.20	7.4	7.1	7.2	7.1
6	10	1.50	7.6	7.2	7.2	7.2

Considering $P_H = 7$ to indicate a state of neutrality, a glance at this table shows that a field application of 7 or 8 tons of lime carbonate per acre would be necessary to insure a slightly alkaline soil reaction for approximately the growing period of a crop. The fact that larger and larger amounts of lime are required upon standing would indicate that hydrogen-ions are being progressively and rapidly formed. This may be due to a decomposition of organic matter with subsequent formation of nitric acid and the less soluble organic acids, to silicate degradation, or to the hydrolysis of soluble aluminum compounds.

* Recent work[4, 24] has intimated that there may be a relation between P_H and lime requirement, whereby the latter may be indirectly and rapidly determined, but it appears to the writer, as well as to Knight,[27] that much work still remains to be done before any general comparisons are possible.

Variability of the Field Soil

It is in no wise the intention of the writer to enter into a detailed discussion of the factor of variability as applied to the study of field soils. The work herein reported was planned for other purposes. Variability studies have been recently attempted by Waynick[47] and by Waynick and Sharp[48] with some measure of success. That seemingly uniform soils may vary greatly both chemically and biologically within very small areas has been well and forcibly brought out by these investigators, and, as an excellent opportunity was here presented for obtaining further data along this line (where water extracts were concerned), a number of analyses are reported showing, for the field soil under discussion, the varying tendencies of the "total soluble solids," the Ca-, K-, NO_3-, and the Cl-ions. The location chosen for the field plot experiment was the area whence these samples came and was in all respects as uniform in texture, color, and appearance as one could well find. It was unusually level, being comparatively free from slight local elevations or depressions so often present in otherwise uniform fields. For miles in all directions but slight visible differences could be detected. The locations of samples are shown in the accompanying diagram of the field plots.

Diagram of Field Plots

1-10th acre plots					1-5th acre plots				
x	x	6	x	x	x	x	9	x	x
x	x	5	x	x	x	x		x	x
x	x	4	x	x	x	x	8	x	x
x	x	3	x	x	x	x		x	x
x	x	2	x	x	x	x	7	x	x
x	x	1	x	x	x	x		x	x

Table IV presents the analytical results secured. Before computing the results as presented, they were in each case plotted and shown to form a proper frequency curve. This justifies the use of the statistical method in connection with these data.

As will be seen, not all of the 48 samples were analyzed in each case, but sufficient determinations were made to show prevailing con-

ditions. As duplicate extractions of the same sample seldom varied by more than 8% to 10% for any of the ions determined (and often by much less), and as the coëfficient of variability (which is nothing more than the standard deviation expressed as its percentage of the mean or arithmetical average) varies from 12% in the case of K-ion to over 44% in the case of NO_3-ion, there can be no doubt that apparently uniform field soils are likely to vary greatly from place to place in water-soluble constituents; and it is evident that only averages of very large numbers of single determinations or analyses of carefully composited samples drawn from a considerable number of separate, uniformly distributed stations over areas under examination can give dependable results or significant differences. Thus the work of

TABLE IV

Variability of the Field Soils as Regards Minerals

(Parts per million of dry soil)

Calcium-ion (Ca)	Potassium-ion (K)	Total Sol. Solids	Nitrate-ion (NO_3)	Chloride-ion (Cl)	Sulfate-ion (SO_4)
62	57	3215	310	120	986
49	54	2540	265	111	520
51	44	2350	288	110	296
48	61	2125	350	120	444
340*	44	3175	243	125	574
55	44	2300	177	130	499
59	54	2300	199	120	355
59	44	1975	133	130	383
278*	53	2500	221	125	316
92	56	2000	203	125	358
440*	48	1950	350	111	432
55	44	1475	203	125	327
60	48	3075	221	310*	381
55	55	2175	420	110	361
66	42	1825	310	105	449
52	39	2675	265	95	358
62	44	1800	221	95	419
59	46	2700	203	100	386
51	49	1975	203	95	363
50	40	1525	111	93	367
70	49	1250	88	90	399
63	48	3000	99	85	385
481*	42	1825	88	75	348
50	39	—	111	80	366
201*	56	Mean = 2244 ± 74	221	100	460
69	56	S.D. = 527 ± 52	133	90	424
60	55	C.V. = 23.5 ± 2.3%	155	95	659
56	53	P.E. = ± 355	111	100	378
87	—		97	90	388
75	Mean = 49 ± .67		97	85	658
69	S.D. = 6 ± .53		177	86	399
191*	C.V. = 12.2 ± 1.1%		115	90	644
—	P.E. = ± 4.0		177	100	392
Mean = 61 ± 1.5			142	150	409
S.D. = 10.9 ± 1.1			97	95	611
C.V. = 18 ± 1.7%			115	75	457
P.E. = ± 7.4			350	85	—
			155	100	Mean = 428 ± 10.9
			155	100	S.D. = 95 ± 7.7
			111	75	C.V. = 22.3 ± 1.8%
			—	—	P.E. = ± 64.4
			Mean = 192 ± 9.2	Mean = 102 ± 1.9	
			S.D. = 86 ± 6.4	S.D. = 17.6 ± 1.3	
			C.V. = 44.8 ± 3.4%	C.V. = 17.2 ± 1.3%	
			P.E. = ± 58.0	P.E. = ± 11.8	

*Omitted from mean.

Waynick and Sharp on soil variability* has been confirmed and shown to hold for certain water extractable materials as well as for nitrates, total nitrogen and organic carbon.

Results of the Plot Experiments

A brief history of the management of the area under study follows:

1913 and 1914: Reclaimed from salt marsh by diking and drainage.

1915: Planted to grain hay. Good yields (3 to 3½ tons per acre).

1916: Planted to peas. Failure.

1917: About one ton per acre of "beet-lime" (85% $CaCO_3$) added and peas again planted. Failure.

1918: Planted again to peas. At first the crop came along nicely, but about the middle of March, when the peas were two-thirds grown, they suddenly began to die out. Small application of lime apparently had little effect. The crop was a failure. After the peas failed the land was immediately plowed and beans were planted. A very poor crop resulted—about 700 pounds per acre.

1919: Sugar beets were grown. A poor crop resulted (between 3 and 4 tons of small beets per acre).

1920: A large part of the poor land was again planted to sugar beets.

Much care was exercised in locating the experimental plots and in their subsequent oversight and treatment. Neither fertilizers nor soil amendments had previously been applied to this area, although small applications (1 ton per acre) of lime had been used on adjacent sections. About one and one-fifth acres (a piece 125 x 450 feet) was measured off during the month of July, 1919, and after the removal of a poor crop of sugar beets, was plowed and disked prior to planting. Six one-tenth acre plots, 20 x 218 feet,† were laid out as were also three one-fifth acre plots, 40 x 218 feet (see diagram above). The smaller plots were numbered from one to six, and superphosphate (18.1% water-soluble and 20.0% total P_2O_5) at the rate of 1 ton per

* For a full and detailed account of the statistical method as applied to the interpretation of biochemical results the reader is referred to the papers of Waynick already cited, to Wood,[50, 51] and to Davenport.[10]

† The plots were made long and narrow to facilitate working and harvesting by standard machinery. Lyon[30] has also shown that long and narrow plots give most dependable results.

acre was applied to the odd plots while the even ones received no treatment (checks). The center one-fifth acre plot (Number 8) was left untreated while Number 7 received finely ground limestone (99.6% $CaCO_3$) and Number 9, sugar beet lime (87% $CaCO_3$), both at the rate of 10 tons per acre. These applications were slightly in excess of the lime requirements for the surface soil (see page 348). The phosphate and lime applications were thoroughly disked into the surface soil about two weeks before planting.

The peas (Horseford's Market Garden Variety) were planted on October 26, 1919, in rows 30 inches apart, one inch apart in the rows. There were thus 8 rows in the smaller and 16 rows in the larger plots.

Since an important part of the plot experiment was the observation of the varying concentration of the soil solution under both the fertilized and the untreated peas (as manifested by periodical analyses of soil extracts prepared from carefully taken representative soil samples), samples, taken as previously described, were drawn and analyzed on September 3, after the plots had been prepared but before the superphosphate had been applied, and subsequently as the data in Table V show. (See also graphs in figs. 3 and 4.)

TABLE V

PERIODIC LABORATORY DATA ON FIELD PLOT SOILS

Dates of Sampling Soils	Conductivity Measurements. Specific Resistance in Ohms		Determinations of Plant Food Ions (p. p. m. dry soil)									
			Ca-Ion		Mg-Ion		K-Ion		NO_3-Ion		PO_4-Ion	
	1	2	1	2	1	2	1	2	1	2	1	2
9–3–19	3000	3000	61	61	45	45	49	49	150	150	5.2	5.2
11–3–19	2560	1382	75	153	46	136	45	99	133	177	5.2	19.5
1–20–20	2430	1497	54	134	42	109	51	83	155	177	4.6	8.7
2–21–20	2970	1855	50	160	34	106	47	83	133	133	1.5	4.5
3–27–20	2495	1792	56	167	52	113	54	83	49	35	2.3	3.7
4–26–20	3965	2162	26	96	20	74	32	58	0	5	2.0	3.0
5–24–20	3258	1895	46	150	37	93	36	54	10	5	2.3	2.8

In all cases No. 1 = check plots and No. 2 = phosphate-treated plots.

As the rainfall during the year 1919–1920 was below the normal average for Marin Meadows Ranch,* and as the growth of the peas

* The annual rainfall data for the past seven years, September 1 to September 1, follows:

1913–1914	35.79 inches
1914–1915	32.99 inches
1915–1916	27.31 inches
1916–1917	14.19 inches
1917–1918	9.20 inches
1918–1919	17.99 inches
1919–1920	11.39 inches

was so largely dependent upon this factor, it was not thought always desirable to draw soil samples at exactly four-week intervals. The following brief summary shows the sampling dates and correlates with these the condition of the peas at those times.

September 3, 1919: First samples drawn. Plots staked out but no fertilizers yet applied.

November 3, 1919: First sampling since planting. As less than 0.3 of an inch of rain had fallen since planting, but few of the seeds had sprouted.

January 20, 1920: The peas were 2 to 3 inches high and a good stand had been secured. Over 4 inches of rain had fallen since last sampling, but the nights were cold (often below freezing), and the days were usually cloudy and cold.

February 21, 1920: Less than one inch of rain had fallen since January 20. The soil was very dry (moisture determinations showed but 27% in the surface soil and 42% in the subsoil). The plants had grown but an inch or two during the month and were often more or less wilted during the middle of the day. The nights were cold. Poor conditions for growth. There was no difference between the checks and the phosphate-treated plots.

March 27, 1920: The plants were looking well. About 3 inches of rain had fallen since last sampling. The vines on the check plots were 6 to 8 inches high while those on the phosphate-treated plots were 10 to 12 inches high. The lime-treated plots showed no improvement over the checks.

April 26, 1920: The plants were looking fairly well, although little rain had been recorded during the month past. The vines were covered with blossoms and filling pods. There was a noticeable difference in favor of phosphate-treated plots although the lime-treated plots showed no gain.

May 24, 1920: Peas about ready to cut. Vines turning yellow; pods well filled and dry. The soil had dried out and was very parched and hard. This was the last date of sampling.

The plots were harvested June 3. The yields obtained are shown in Table VI.

TABLE VI

PLOT YIELDS

	Gross Weights, Dry Peas and Vines		Net Weights, Dry Peas	
	lbs.	lbs. per acre	lbs.	lbs. per acre
Average yield per 1/10 acre plot (checks)	627	6,270	153	1,530
Average yield per 1/10 acre plot (superphosphate)	820	8,200	200	2,000
Average yield per 1/5 acre plot (checks)	1,010	5,050	340	1,700
Average yield per 1/5 acre plot (sugar beet lime)	1,090	5,450	340	1,700
Average yield per 1/5 acre plot (ground limestone)	1,090	5,450	330	1,650

It will be seen that liming to neutrality had no effect upon yields. This is in accordance with former field observations on this soil. A more extended discussion of the effects of the application of lime

will be given later in connection with results secured in the greenhouse where moisture conditions were optimum and where a more careful chemical control was possible. The superphosphate treatment increased the yield of peas by approximately 25 per cent. This increase about paid for the treatment, and a future residual effect may be expected. Possibly a larger amount of superphosphate would have given higher yields, for much was lost due to reversion (see below).

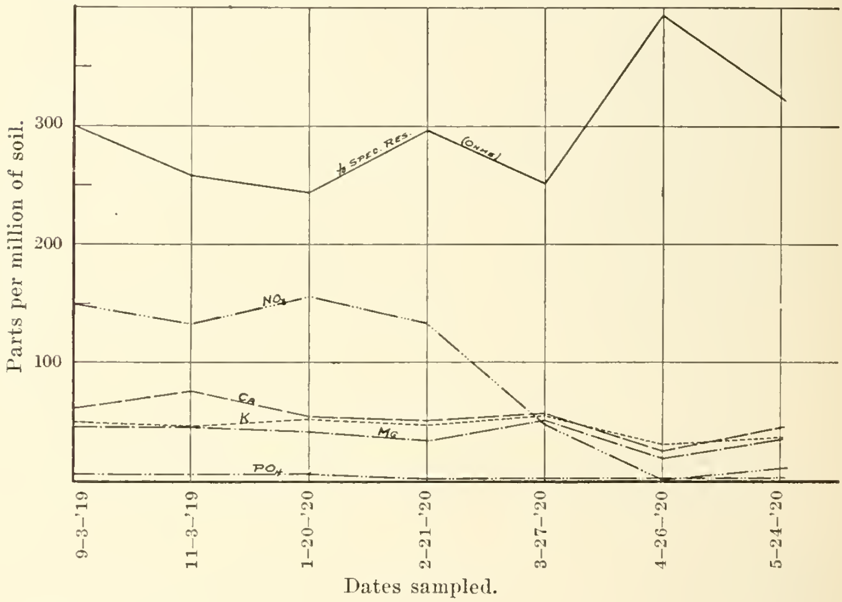

Fig. 3.—Water-soluble materials dissolved from unfertilized plot soils carrying pea crop.

As has been mentioned, the rainfall was subnormal throughout the entire growing period. That the low yields secured on both treated and untreated plots were attributable in large part to a lack of water will be shown by the following test. Four approximately 50-foot rows (two in a phosphate plot and two in a check plot) were chosen at random and regularly irrigated* for a period of several weeks during the months of February and March. Rapid growth and great improvement over those plants not so treated was observed. As heavy rains fell during the latter part of March, irrigating was discontinued. The beneficial results of these few applications of water during the early stages of growth were, however, noticeable up to the time of harvesting.

* Water hauled in a tank wagon.

The curves presented in figures 3 and 4 show graphically the rise and fall in concentration of the soil solution under the growing crop. In studying these graphs it should be remembered that the superphosphate was applied between September 3 and November 3 (see figure 4), and that the plants were absorbing nutrients most vigorously during the months of March and April. We note first that much greater concentrations of salts prevail throughout the entire period within the soils of the fertilized plots. This is clearly depicted by the solid line

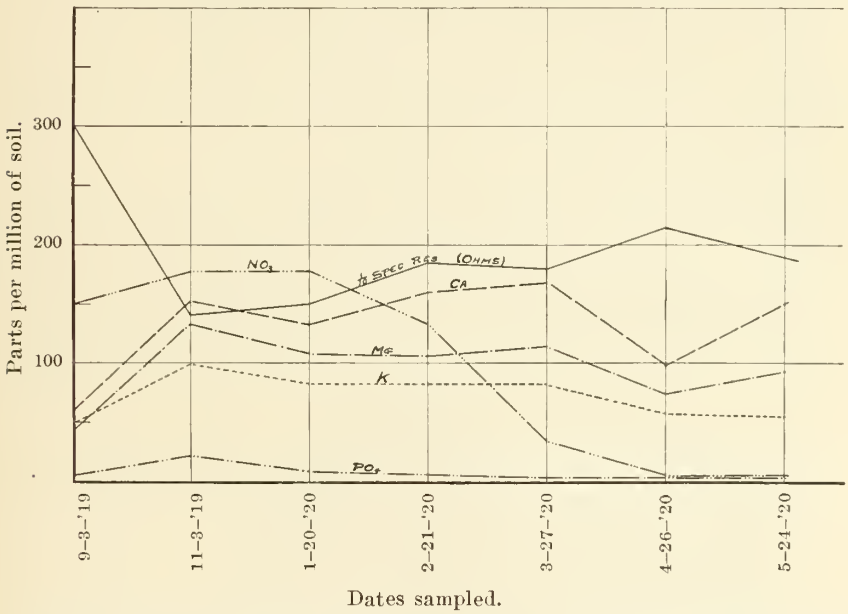

Fig. 4.—Water-soluble materials dissolved from phosphate-treated plot soils carrying pea crop.

representing one-tenth of the specific resistance in ohms. That this increased concentration is due in large part not to the superphosphate, but to the increased solubility of other ions caused by it within the soil itself, is strikingly shown by the Mg and K graphs. This doubtless accounts largely for the greater yields obtained on the phosphate plots, for where water is limited, Morgan[37] has shown that transpiration is necessarily less, and that the enhancing effect of fertilizers is relatively greatly increased. He states, "All fertilizers, both mineral and nitrogenous, have greatly decreased in their relative efficiency following an increase in soil moisture. The decrease is consistent." It is further a well established physiological fact that water is greatly economized by increasing the plant's supply of mineral salts (see Russel,[40] pages 29, 30).

Taking up the ions separately, we note that phosphate applications have but slightly affected nitrate formation. This is doubtless due to excessive soil acidity which dominates nitrification within this soil.

The yields show that soluble nitrogen is here more than adequate for peas. The amounts of potassium and magnesium, soluble in water, in this heavy clay soil, have been almost doubled throughout the entire growing period by the initial acid-phosphate application. That the gypsum present in the superphosphate is largely responsible for this increase is shown by results secured in the more carefully controlled greenhouse experiment (see McCool and Millar[33] in this connection). As would be expected, both water-soluble calcium and phosphorus have been somewhat increased in the soils of those plots receiving the soluble phosphate treatments.

Chlorides and sulfates were periodically determined. As these ions were always present in great excess, however, they have not been included in Table V nor in the graphs, but have been more properly figured as the sodium salts (white alkali), and appear in Table VII. An idea has prevailed in the past that occasional increases in the amount of alkali present may have been responsible for crop failures.

TABLE VII

PERIODICAL DETERMINATION OF WHITE ALKALI IN PLOT SOILS

Date	% NaCl	% Na_2SO_4
September 3, 1919	0.018	0.066
November 3, 1919	.025	......
January 20, 1920	.023	.066
February 21, 1920	.017	.067
March 27, 1920	.032	.060
April 26, 1920	.017	.050
May 24, 1920	.020	.100

While the percentages of alkali here noted are doubtless innocuous if optimum moisture conditions exist, it is conceivable, as before stated, that at times of unusual drought, plants may suffer in the more concentrated soil solution that results, and, while a lack of water is directly responsible for this condition, alkali salts may well be considered an important indirect or contributing factor.

Other toxic compounds, as ferrous iron* or soluble aluminum salts, here appealed to the writer as being possible causes of infertility. We were, however, unable to secure a positive test for ferrous iron in the surface soil. Special samples were taken for these tests, every

* Certain heavy soils of the Transvaal have been shown by Watt[46] to have been rendered unproductive by accumulations of ferrous salts.

precaution being used to avoid oxidation in transit. On the other hand, water-soluble aluminum was usually found. Large numbers of determinations showed it to be present to the extent of 12 to 15 parts per millon in the surface soil, while approximately twice these amounts were found in the subsoil.

The considerable literature upon the subject of aluminum toxicity has been notably extended during the past two or three years by the careful work of Hartwell and Pember,[17, 18] Conner,[9] Ames and Schollenberger,[2] and Miyake.[35] The first-mentioned investigators have definitely shown that soluble aluminum compounds exist in toxic concentrations in certain acid soils; that plants differ in their powers of resistance to soluble aluminum; and that such conditions may be readily ameliorated by applications of any substance which will precipitate aluminum-ion. From data furnished by Hartwell and Pember[18] (page 266), it is possible to calculate the concentration of soluble aluminum present in the acid soils upon which they experimented. This was found to be approximately 77 parts of Al_2O_3 or 41 parts of soluble aluminum per one million parts of dry soil. They extracted using slightly different proportions (about 1 to 3) of soil and water than did the writer, but the results should be fairly comparable. They furthermore found that at least 15 p. p. m. of aluminum in solution cultures with growing plants were required to produce signs of toxicity. In the light of these results, it would appear somewhat doubtful whether the relatively small quantities (12 to 15 p. p. m. of aluminum) found in the soil of the Marin Meadows Ranch could be entirely responsible for the seriously depleted yields. The other authors cited in this connection have shown that amounts of aluminum greatly in excess of 15 p. p. m. of soil are necessary to render conditions toxic for crop plants in soils; and, finally, the plants in our own untreated pots, in which this soil was used without drainage, gave no indications of aluminum-poisoning.

To sum up briefly the points brought out by the field plot experiment, we may conclude with reasonable certainty that, during the past season at least, water has been the limiting factor in crop production; that a one-ton application of superphosphate in absence of irrigation has increased the yield of peas by approximately 25 per cent; that liming to neutrality had practically no effect upon yield, due possibly to delayed reaction on account of paucity of rainfall; and, finally, that inorganic toxins, as alkali, ferrous iron, and aluminum salts, are probably at present not directly responsible for lack of productivity.

THE GREENHOUSE EXPERIMENTS

While field trials are generally considered as being the most reliable method of solving fertility problems, they are expensive and cumbersome, and, as has already been shown, should be executed over a period of years to allow for a fair average of climatic conditions. The quicker, less expensive, and more controllable pot experiment, as carried out in a well equipped greenhouse, is therefore often desirable. Coffey and Tuttle,[7] Wheeler, Brown and Hogensen,[49] and others have compared pot tests with field trials and have shown them to agree remarkably well where certain details of manipulation are followed. Furthermore, the ofttimes limiting factors of moisture and temperature may be so controlled in greenhouse work as to permit of more definite conclusions regarding possible plant food deficiencies. In the present work, this method of experimentation was especially adaptable, as frequent periodical soil-sampling was required.

The proper kind and quantity of fertilizer to apply depend as much upon the *total effect* produced within the soil solution as they do upon the element or elements directly supplied, for many of the changes induced may be indirect. For instance, sodium nitrate, so widely used as a source of available nitrogen, may so deflocculate a heavy soil as to render it non-productive. Much information is at present available in agricultural literature on the effects of additions of fertilizer salts and other chemical compounds upon the solubility of soil constituents. While a large portion of these data have been secured by subjecting the soils studied to artificial laboratory conditions, far removed from those actually obtaining in the field, nevertheless many of them have a sufficient bearing upon the present work to necessitate reviewing. More than seventy articles were read in this connection. However, as comprehensive references to the literature accompany the papers of Greaves and Carter,[13] Spurway,[43] and MacIntire,[31] it was thought best not to burden the reader with an extended review, very little of which could be directly compared with data to be subsequently presented, but rather to give a brief discussion of the work as a whole, noting the points in agreement as well as those at variance with the results hereafter given.

The chief impression made upon the reviewer of the literature within this field is the dissimilarity and often contradictory nature of results reported. For instance, certain writers have shown that additions of sodium nitrate to soils greatly enhance phosphate availability,

while a like number may easily be found who claim that sodium nitrate inhibits the solution of phosphates in soils. Similar differences of opinion exist regarding the effects of lime and gypsum upon the solubility of soil potash. An able discussion of such discrepancies, at least in so far as the effects of calcium carbonate and gypsum upon soil potassium are concerned, is given by Lipman and Gericke.[29] These writers attribute unlike and contradictory results to variations in the nature of the *mineral content* of the soils from different localities. The linkages binding potassium within the intricate silicate molecules doubtless vary greatly with different mineral complexes, the potassium being much more easily replaced by calcium, sodium, or other metallic ions in some instances than in others. As this might equally well apply to all the elements ordinarily met with in soils, one could hardly expect similar results to be obtained in all cases and for all elements. In fact, Lipman and Gericke,[29] Spurway,[43] Christie and Martin,[6] and many others give data which conclusively show that applications of the same salts in similar amounts react differently in different soils. Another factor which doubtless also plays a part is soil texture. The fine clays and clay loams presenting many times the internal surfaee found in the coarser silts and sands, should, and usually do, yield more material to solution. This is probably largely a mechanical factor.

Taking the recorded data on this subject by and large, the following statements seem to be justified in a majority of cases. The normal sulfates and chlorides of calcium, magnesium, sodium, and ammonium, may enhance the solubility of soil potassium and soil phosphorus, although the acid salts act much more strongly, especially in the case of the latter element. Nitrates act erratically, but we are fairly safe in saying that they usually slightly increase soil potash solubility, and exert little effect on soil phosphorus, although we know that the calcium phosphates are much more soluble in solutions of nitrates than are the iron and aluminum phosphates. The addition of calcium oxide usually increases potash solubility while the carbonate often has no direct effect. Phosphate solubility is usually depressed by lime applications, although this is not universally the case with quicklime, while the sulfates of the heavy metals often greatly increase it. Many writers have also shown that, under certain conditions, the soil bacteria, especially the nitrifiers, exert a decided solvent aetion upon the insoluble phosphates of both soils and fertilizers.

Objects of the Pot Experiments

The objects of the pot experiments hereafter reported were: (1) so far as possible to eliminate climate, especially moisture, as a factor in crop production upon the soil studied, and to maintain throughout the growth period as nearly optimum conditions as possible; (2) to note the effects upon the growth of the pea plants, and upon the final yields of dried peas, of additions of the several fertilizers and soil amendments supplied; (3) to find whether or not such applications of chemical compounds influence the solubilities of the soil's constituents as manifested by periodical extractions of both planted and fallowed soils with distilled water; (4) to ascertain the effect of soluble salt applications upon the nodule formation of peas within this acid soil; (5) to ascertain whether or not soil toxins of any kind were inhibiting normal growth.

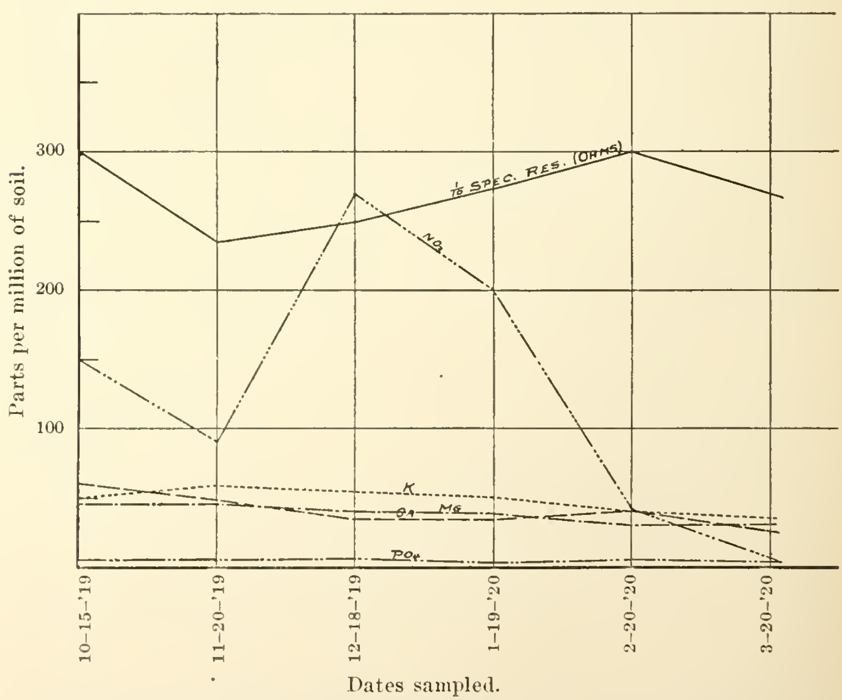

Fig. 5.—Water-soluble materials dissolved from cropped check pot soils (no fertilization).

Treatments Employed

The experiments were carried out in a well regulated greenhouse. The pots used were 5-gallon glazed earthenware crocks about 12 inches in diameter and 11 inches deep. No holes were provided for drainage as it was desired that no soluble constituents be lost during the growth of the crops. The pots were weighed, and water added to optimum at

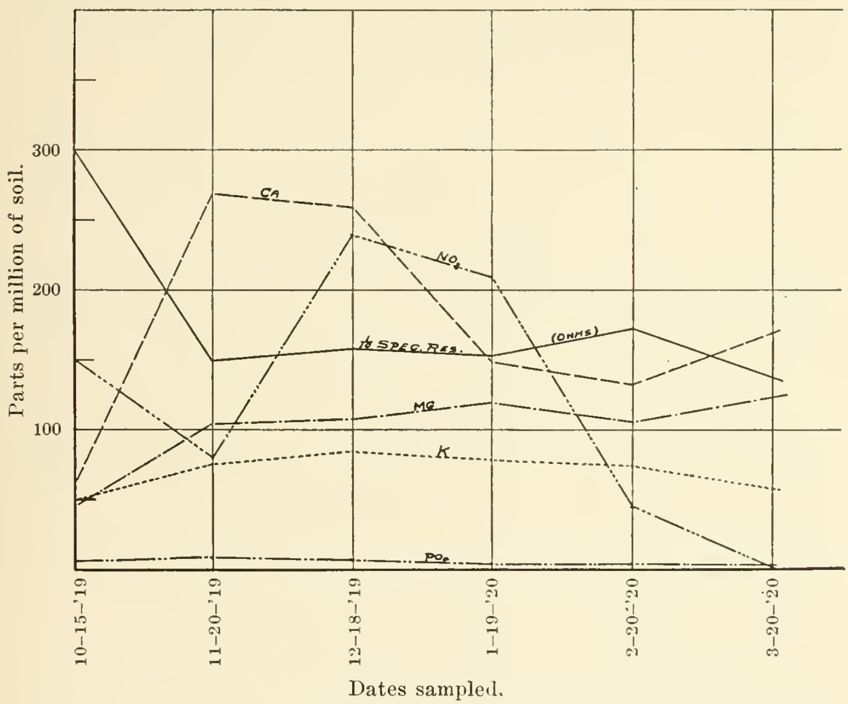

Fig. 6.—Water-soluble materials dissolved from cropped gypsum-treated pot soils.

each irrigation. The soil was procured during the month of August from the field plots above described, 6 two-bushel sacks of surface soil being taken from each of the 6 one-tenth acre plots. It was air-dry and dusty to a depth of approximately 6 inches. When received at the greenhouse, it was thoroughly mixed by being shoveled over five times and twice screened (one-fourth inch mesh) to remove the larger clods. Thirteen kilograms were then weighed into each of 64 pots, thus providing eight pots for each of the eight different treatments to be tested. The additions were made as follows:

Pots 1– 8: Checks. No additions.
Pots 9–16: Gypsum at the rate of 1 T. per acre (20 g. per pot).
Pots 17–24: $CaCO_3$ at the rate of 8 T. per acre (160 g. per pot).
Pots 25–32: Superphosphate at the rate of 1 T. per acre (20 g. per pot).
Pots 33–40: $NaNO_3$ at the rate of 500 lbs. per acre (5 g. per pot).
Pots 41–48: K_2SO_4 at the rate of 500 lbs. per acre (5 g. per pot).
Pots 49–56: Super. (1 T. per a.) and K_2SO_4 (500 lbs. per a.).
Pots 57–64: Super. (1 T. per a.) and $CaCO_3$ (8 T. per a.).

As will be observed, the applications here made were in all cases consistent with good field practice. The amounts of salts (dry) as indicated were thoroughly mixed into the surface six inches of soil

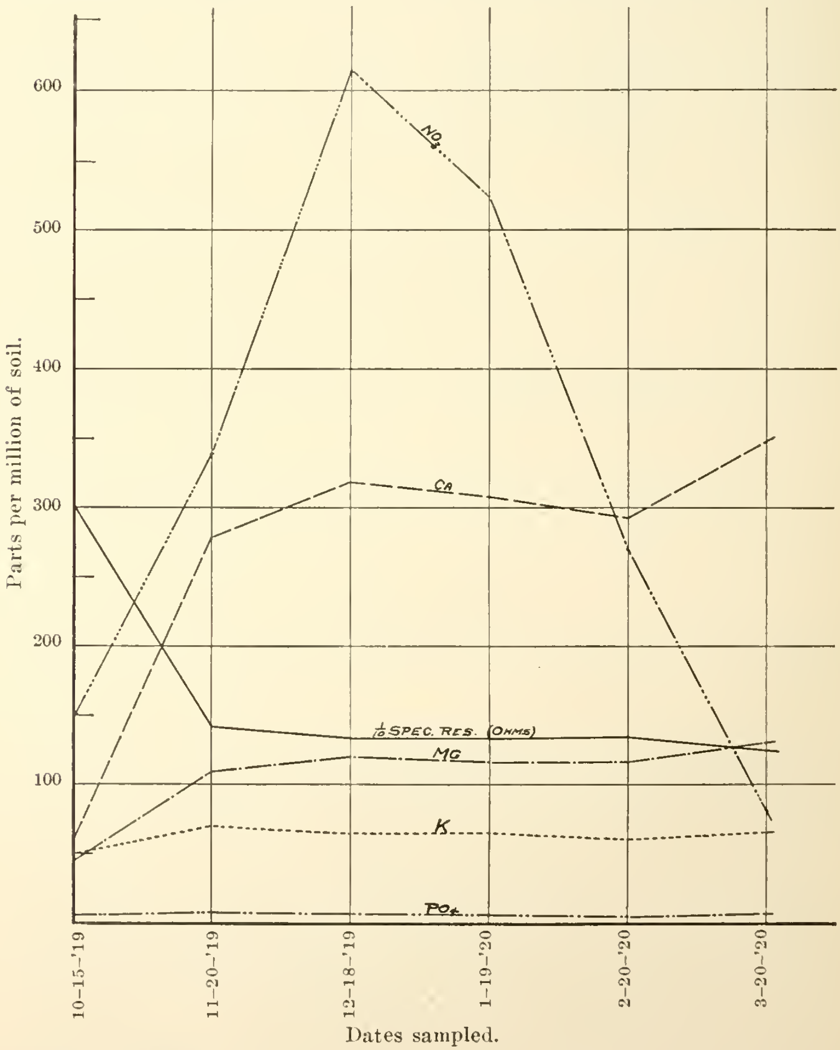

Fig. 7.—Water-soluble materials dissolved from cropped calcium-carbonate-treated pot soils.

in each pot, after which the soils were settled into place by an irrigation calculated to be optimum (one-half total moisture holding capacity). The pots were then allowed to stand for one week before planting. The salts applied were ''Bakers C. P. Analyzed Chemicals'' in all cases except the superphosphate, which was the same as that used in the field plot experiments. At the same time, a set of six pots of the soil, which were to be kept fallow (no crop) were set up. The first six, single-salt treatments only were here employed. These fallowed pots were subsequently treated in exactly the same way as the cropped pots.

The peas (Horseford's Market Garden variety) were sown on November 10, 1919; eight uniform seeds to the pot. A good stand was obtained. When the plants were about three inches high, they were thinned to four per pot. When 6 to 8 inches high, the peas were trellised, using split laths and string. The floor plan of the greenhouse indicating the arrangement of the benches and the pots is shown in figure 2. As the plants grew taller and shading was evident at certain periods during the day, the practice of changing the pots from one bench to the other each week at the time of irrigation was adopted.

As one of the objects of the work was to ascertain the effects of the several salt applications upon soil-mineral solubility, at approximately four-week intervals samples of the cropped soils were withdrawn from the pots and analyses made in accordance with the detailed methods previously given. The results of this work appear in Table VIII and, for convenience, are graphically shown in figures 5 to 19. It had been planned also to extract and analyze the similarly treated fallowed soils each month, but, as the two series will be shown to be hardly comparable, and as time for this large amount of analytical work was wanting, the uncropped soils were analyzed but four times during the experiment (during October, November, January, and April). The results of these analyses appear in Table IX.

After thinning, and when the plants had reached a height of 6 or 7 inches, some trouble was experienced with mice. In eight or ten of the pots, one or two of the plants were destroyed. This difficulty was quickly overcome, but not before some damage had been done. For this reason, in Table X, only six pots (out of the eight of each treatment) giving the highest yields per pot, and having four plants each, have been used in computing statistically the final yields obtained, although the yields in all of the pots are given.*

* As stated in the table, a star (*) marks those figures omitted from the averages. The data, when plotted, gave uniform frequency curves.

TABLE VIII

PERIODIC DETERMINATIONS ON CROPPED, POT SOILS

Treatment Number	Dates of Sampling Soils 10–15–19	11–20–19	12–18–19	1–19–20	2–20–20	3–20–20
			Acidity expressed in P_H			
1	4.46	4.51	4.50	4.48	4.46	4.71
2	4.46	4.55	4.58	4.50	4.51	4.73
3	4.46	7.20	7.20	7.39	7.34	7.25
4	4.46	4.67	4.62	4.62	4.60	4.71
5	4.46	4.67	4.72	4.53	4.63	4.88
6	4.46	4.67	4.68	4.67	4.67	4.88
7	4.46	4.63	4.63	4.63	4.65	4.80
8	4.46	7.30	7.33	7.46	7.42	7.33
			Specific Resistance in Ohms			
1	3,000	2,381	2,515	2,752	3,053	2,726
2	3,000	1,498	1,568	1,517	1,728	1,402
3	3,000	1,420	1,331	1,325	1,357	1,261
4	3,000	1,280	1,568	1,856	2,022	1,587
5	3,000	2,112	2,029	2,131	2,374	2,302
6	3,000	2,131	2,054	2,400	2,509	2,118
7	3,000	1,286	1,472	1,523	1,702	1,382
8	3,000	1,171	1,133	998	1,088	1,018
			Calcium-ion, parts per million			
1	60	49	35	34	41	25
2	60	269	262	150	133	169
3	60	279	319	309	295	350
4	60	131	136	104	88	128
5	60	59	59	50	43	48
6	60	169	71	55	52	56
7	60	160	150	121	102	169
8	60	387	430	428	434	500
			Magnesium-ion, parts per million			
1	45	46	40	37	30	29
2	45	105	109	120	107	125
3	45	110	121	117	116	130
4	45	110	106	79	78	102
5	45	55	53	48	46	38
6	45	70	67	56	48	55
7	45	133	125	98	86	127
8	45	145	147	144	150	154
			Potassium-ion, parts per million			
1	50	58	54	50	39	35
2	50	75	84	80	75	60
3	50	69	64	65	60	63
4	50	87	81	68	51	61
5	50	65	66	58	41	37
6	50	88	86	75	58	63
7	50	117	117	97	70	92
8	50	75	69	74	56	65

TABLE VIII—(*Continued*)

Treatment Number	Dates of Sampling Soils 10–15–19	11–20–19	12–18–19	1–19–20	3–20–20	3–20–20
	Phosphate-ion, parts per million					
1	5.2	3.7	4.5	2.3	3.5	2.1
2	5.2	6.2	5.6	4.0	4.0	3.4
3	5.2	6.2	4.7	4.5	4.1	5.4
4	5.2	8.5	6.8	8.4	7.2	4.1
5	5.2	5.6	5.9	4.1	4.3	2.3
6	5.2	5.6	5.6	4.7	4.5	2.0
7	5.2	7.4	7.0	7.4	6.9	3.2
8	5.2	7.6	6.7	7.8	7.0	5.6
	Nitrate-ion, parts per million					
1	150	89	267	204	35	5
2	150	80	239	213	44	0
3	150	338	621	532	266	84
4	150	156	221	177	27	0
5	150	488	488	400	177	30
6	150	178	266	177	44	5
7	150	156	266	177	40	7
8	150	196	485	443	266	156

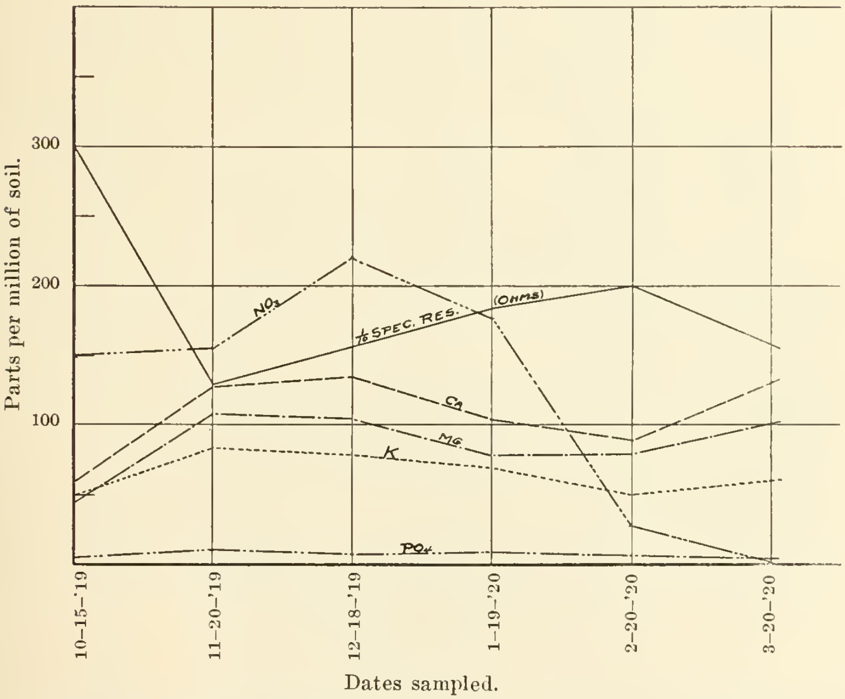

Fig. 8.—Water-soluble materials dissolved from cropped superphosphate-treated pot soils.

TABLE IX

PERIODIC DETERMINATIONS ON FALLOWED, POT SOILS

Treatment Number	Dates of Sampling Soils 10–15–19	11–20–19	1–25–20	4–1–20
	Acidity expressed in P_H			
1	4.46	4.50	4.43	4.32
2	4.46	4.55	4.50	4.38
3	4.46	7.20	7.17	7.17
4	4.46	4.67	4.46	4.46
5	4.46	4.67	4.45	4.43
6	4.46	4.67	4.40	4.38
	Specific Resistance in Ohms			
1	3,000	2,380	lost	2,048
2	3,000	1,498	lost	1,338
3	3,000	1,420	lost	1,011
4	3,000	1,280	lost	2,180
5	3,000	2,112	lost	1,587
6	3,000	2,131	lost	1,754
	Calcium-ion, parts per million			
1	60	49	72	81
2	60	269	250	209
3	60	279	514	512
4	60	131	112	99
5	60	59	104	100
6	60	169	128	104
	Magnesium-ion, parts per million			
1	45	46	67	80
2	45	105	147	161
3	45	110	144	157
4	45	110	105	105
5	45	55	86	96
6	45	70	67	98
	Potassium-ion, parts per million			
1	50	58	58	59
2	50	75	86	84
3	50	69	65	59
4	50	87	81	73
5	50	65	68	72
6	50	88	86	96
	Phosphate-ion, parts per million			
1	5.2	3.7	3.7	2.3
2	5.2	6.2	4.1	2.4
3	5.2	6.2	4.5	4.3
4	5.2	8.5	8.4	8.8
5	5.2	5.6	5.6	4.1
6	5.2	5.6	4.7	2.3
	Nitrate-ion, parts per million			
1	150	89	400	575
2	150	80	756	708
3	150	338	1,264	1,106
4	150	156	550	496
5	150	488	421	940
6	150	178	355	575

Crop Yields

The effects of the several soil treatments upon crop yields will first be considered. Table X presents this data while a chart showing graphically the comparative yields of both total dry matter and cured peas appears in figure 20. The "plus or minus" variability factors as shown in figure 20 are obtained by multiplying the "probable error of the mean" in each case (Table X) by three, thus insuring practically a thirty to one chance that, in case of repetition, the new average yields found will fall within these limits. Those figures also help us in determining approximately* whether or not significant differences in yields are shown between treatments.†

The most notable fact impressed upon one who has carefully followed both the field and the greenhouse experiments is that the plants grown in the greenhouse under nearly ideal climatic conditions grew to at least twice the size and probably, plant for plant, produced nearly twice as many peas as those grown in the field at the Marin Meadows Ranch. Although the crop on the field plots was above the average, the individual plants were small in comparison with any (checks included) grown inside. That water has been one of the important limiting factors in the field during the past season can hardly be questioned.

The second point to be noticed is the comparatively *small* increase over the check pots due to any of the fertilizer applications. One would certainly expect a soil so low in soluble phosphorous or so acid in reaction to respond *greatly* to applications of either soluble phosphates or lime, and certainly where both were used. But no such large increases are apparent. It is true that enhanced yields follow the application of

* The *exact* method of determining whether or not a difference is significant is to take the square root of the sum of the squares of the two probable errors of the two means, multiply the resulting figure by 3 and note whether or not the product is larger or smaller than the subtracted difference between the two means. In case it is smaller, it is safe to conclude that the difference between the two means is significant, taking a 30 to 1 chance of securing a similar result upon repetition. For example, let us compare the average yield of total dry matter secured in the check pots with that where gypsum was applied, and find whether or not gypsum *actually* increased yields:

$$59.5 \pm 0.9 = \text{mean of gypsum pots.}$$
$$51.4 \pm 1.3 = \text{mean of check pots.}$$

$$\begin{aligned} &8.1 \pm \sqrt{0.9^2 + 1.3^2} \times 3 \\ &= 8.1 \pm \sqrt{2.50} \times 3 \\ &= 8.1 \pm 4.6 \end{aligned}$$

As 4.6 is much less than 8.1, we are safe in concluding that there *is* a significant difference shown here between the means, and that the application of gypsum did actually slightly increase yields.

† The scale to the left of fig. 20 should be used in this connection.

TABLE X

YIELDS OF PEAS IN GREENHOUSE POT EXPERIMENT

Treatment No. 1 (Checks)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
1	53.6	37.1	29.7
2	45.1*	28.4*	21.1*
3	58.6	37.7	30.9
4	53.6	34.9	28.9
5	50.7*	38.6*	31.5*
6	51.0	34.5	28.0
7	44.2	33.9	26.1
8	47.2	34.1	28.0
Mean	51.4±1.3	35.4±0.4	28.6±0.4
Std. Dev.	4.7±1.4	1.5±0.4	1.5±0.4
C. V.	9.2±1.8%	4.2±0.8%	5.2±1.0%
P. E.	±3.2	±1.0	±1.0

Treatment No. 2 (Gypsum)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
9	53.7*	34.3*	25.5*
10	55.8	37.3	29.5
11	64.3	37.6	29.8
12	62.9	35.6	28.4
13	59.0	33.0	29.8
14	58.1	36.7	29.7
15	56.6	33.9	26.9
16	56.9*	34.0*	26.4*
Mean	59.5±0.9	35.7±0.4	29.0±0.3
Std. Dev.	3.1±0.9	1.7±0.5	1.0±0.3
C. V.	5.2±1.0%	4.8±0.9%	3.4±0.7%
P. E.	±2.1	±1.1	±0.7

Treatment No. 3 (Calcium carbonate)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
17	68.7*	38.6*	30.6*
18	70.5	42.9	34.6
19	70.6	41.2	33.6
20	70.2	42.8	36.5
21	67.0	40.9	33.3
22	65.0	37.2	31.6
23	69.1	44.2	36.6
24	61.3*	36.5*	29.2*
Mean	68.7±0.6	41.5±0.6	34.4±0.5
Std. Dev.	2.1±0.6	2.2±0.6	1.8±0.5
C. V.	3.1±0.6%	5.3±1.0%	5.2±1.0%
P. E.	±1.4	±1.5	±1.2

Treatment No. 4 (Superphosphate of lime)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
25	58.5	35.8	29.7
26	60.4	36.4	29.7
27	56.3*	34.2*	27.4*
28	68.5	40.8	32.6

* Omitted from average.

TABLE X—(*Continued*)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
29	61.8	36.5	29.9
30	68.6	40.0	32.0
31	69.1	37.8	30.5
32	60.4*	33.4*	27.8*
Mean	64.5±1.2	38.0±0.5	30.7±0.3
Std. Dev.	4.4±1.3	1.9±0.5	1.1±0.3
C. V.	6.8±1.3%	5.0±0.9%	3.6±0.6%
P. E.	±3.0	±1.3	±0.7

Treatment No. 5 (Sodium nitrate)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
33	59.2	36.0	28.7
34	59.9*	32.1*	24.3*
35	60.1	36.9	30.0
36	55.9	33.0	26.5
37	60.5	35.2	29.1
38	54.7	33.4	27.0
39	53.1*	29.0*	23.2*
40	55.0	30.2	25.0
Mean	57.6±0.7	34.1±0.6	27.7±0.5
Std. Dev.	2.4±0.7	2.2±0.6	1.7±0.5
C. V.	4.2±0.8%	6.4±1.2%	6.1±1.1%
P. E.	±1.6	±1.5	±1.2

Treatment No. 6 (Potassium sulfate)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
41	52.8	33.1	26.7
42	54.8	31.4	24.8
43	50.0*	29.4*	23.6*
44	50.6	33.0	26.2
45	56.6	34.4	27.7
46	52.3	31.8	25.9
47	58.6	35.6	30.6
48	54.8*	29.6*	24.5*
Mean	54.3±0.7	33.2±0.4	27.0±0.5
Std. Dev.	2.7±0.8	1.4±0.4	1.8±0.5
C. V.	5.0±0.9%	4.2±0.8%	6.6±1.2%
P. E.	±1.8	±0.9	±1.2

Treatment No. 7 (Super. plus K_2SO_4)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
49	49.7*	28.3*	23.0*
50	47.8	30.1	25.5
51	47.4*	23.3*	18.6*
52	53.5	31.3	25.2
53	57.0	33.1	29.1
54	51.6	31.2	26.2
55	56.7	33.2	27.4
56	57.4	34.8	29.1
Mean	54.0±1.0	32.3±0.4	27.1±0.4
Std. Dev.	3.5±1.0	1.6±0.5	1.6±0.5
C. V.	6.5±1.2%	4.9±1.0%	5.9±1.2%
P. E.	±2.4	±1.1	±1.1

* Omitted from average.

TABLE X—(*Continued*)

Treatment No. 8 (Super. plus $CaCO_3$)

Pot Number	Total Dry Weights	Peas in Pods	Shelled Peas
57	64.7	41.0	34.3
58	54.5*	33.0*	27.9*
59	62.8	38.0	32.4
60	55.9	35.2	30.4
61	54.9*	33.0*	28.2*
62	64.6	42.7	35.7
63	60.6	39.1	33.2
64	71.9	48.2	41.1
Mean	63.4±1.3	40.7±1.1	34.5±0.9
Std. Dev.	4.8±1.4	4.1±1.2	3.3±1.0
C. V.	7.5±1.4%	10.1±1.8%	9.6±1.8%
P. E.	±3.2	±2.8	±2.12

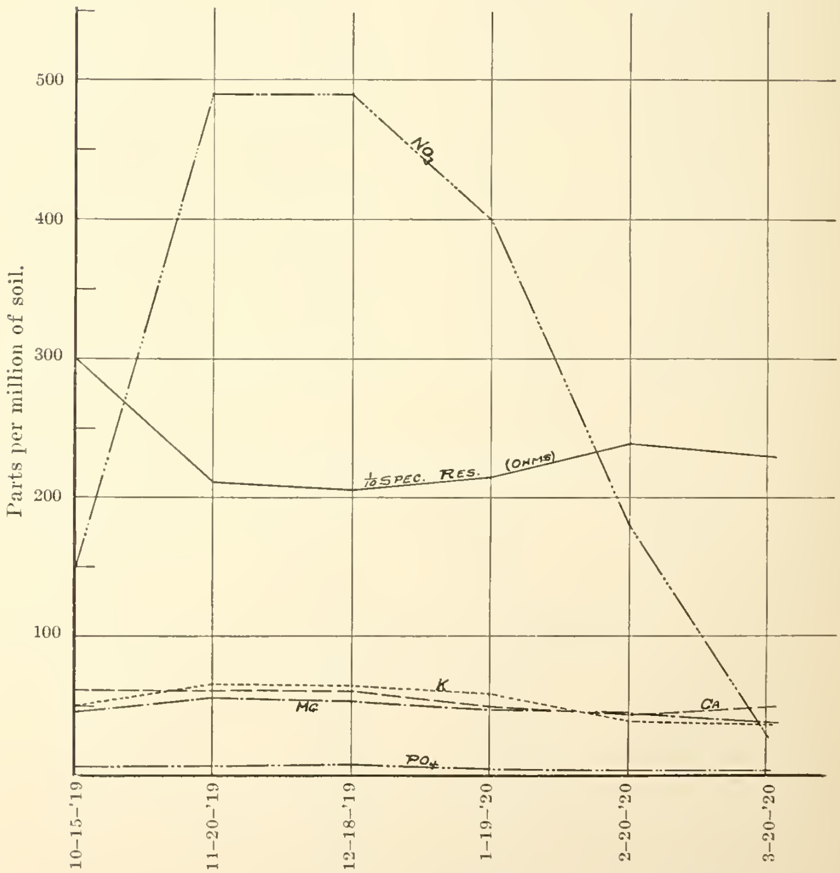

Fig. 9.—Water-soluble materials dissolved from cropped sodium-nitrate-treated pot soils.

* Omitted from average.

certain of these compounds, but they amount to relatively little. Let us observe the chart showing comparative yields (fig. 20), first taking up "Total Dry Weights" produced. Treatment No. 1 (checks) produced lower yields than did any of the others, yet brief computations show that the differences between the checks and treatments 6 (K_2SO_4) and 7 (K_2SO_4 + superphosphate) are not significant, while the real difference between the checks and 5 ($NaNO_3$) is so slight (less than 2

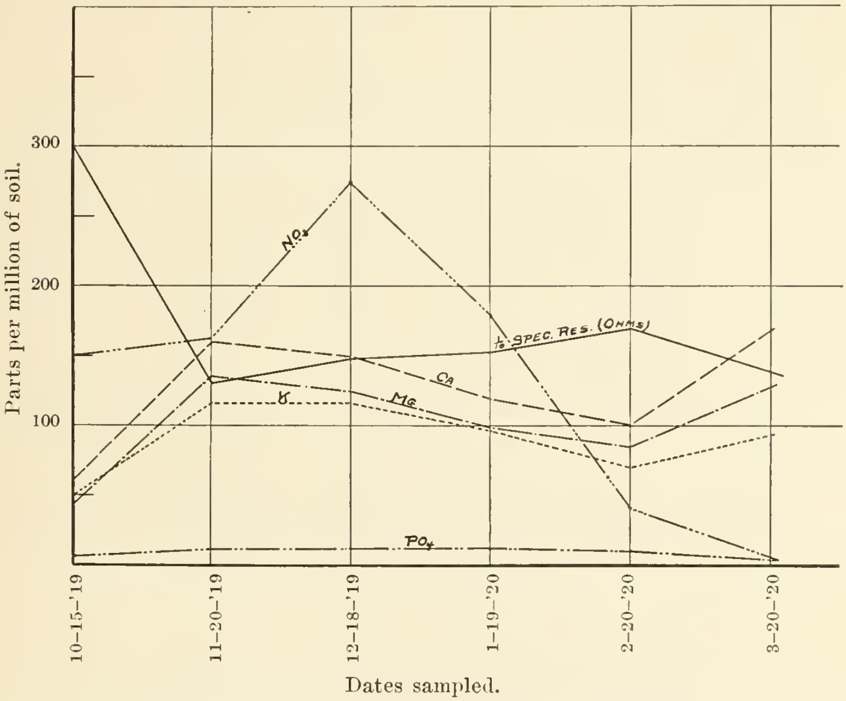

Fig. 10.—Water-soluble materials dissolved from cropped potassium-sulfate-treated pot soils.

grams) as to be well-nigh negligible. We are, however, justified in stating that liming to neutrality did actually increase the yields of peas in the greenhouse over the checks by nearly 35%; that applications of superphosphate, at the rate of one ton per acre, gave an increase of approximately 28%; that the same amounts of superphosphate and $CaCO_3$ when used together increased yields no more than did either when added separately; and that gypsum at the rate of one ton per acre was about one-half as effective as $CaCO_3$ when the latter was used in sufficient quantities to neutralize soil acidity (8 tons per acre). It will be recalled that, in the field, superphosphate alone

gave increased yields, while calcium carbonate, added to neutrality, had little effect. The comparative solubilities of the two, water being limited in the field, may well account for these differences. The final yields of dry matter obtained, however, do not show the comparative *rates* of growth nor do they reflect the conditions of the plants at the various monthly periods of sampling. During the entire experiment

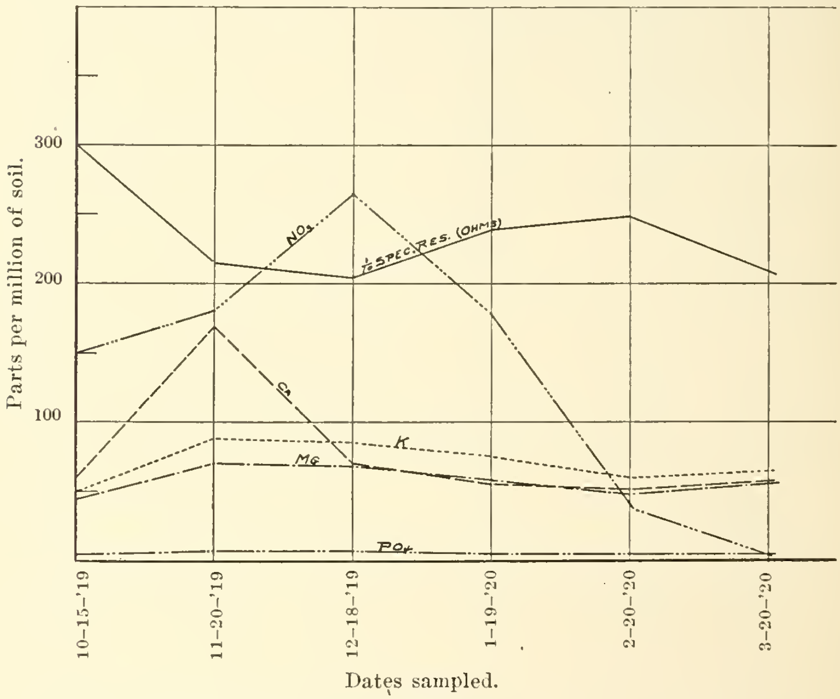

Fig. 11.—Water-soluble materials dissolved from cropped pot soils receiving both superphosphate and potassium sulfate.

the phosphate treated plants were apparently far ahead of all others in size, color, and general condition. They bloomed and set pods at least a week before the other treatments and matured ten days earlier than the others. The nitrate treated plants started well but soon fell behind. The lime treated plants made a slow, steady growth from the start, and, as will be seen, gave maximum yields both of total dry matter produced and of dry peas. Potassium sulfate wherever applied seemed at all times to retard growth. This may be due to the considerable quantity of sulfate-ion added, as the soil already carried nearly one-tenth of one per cent sodium sulfate. Gypsum also at first impeded growth. Figure 21 gives one a good

idea of the plants when the pods were setting (about one month before harvesting). It serves to compare the several treatments, an average pot from each series being taken in each case.

Let us now consider the comparative weights of dried, shelled peas produced by the different salt applications (see fig. 20). The results

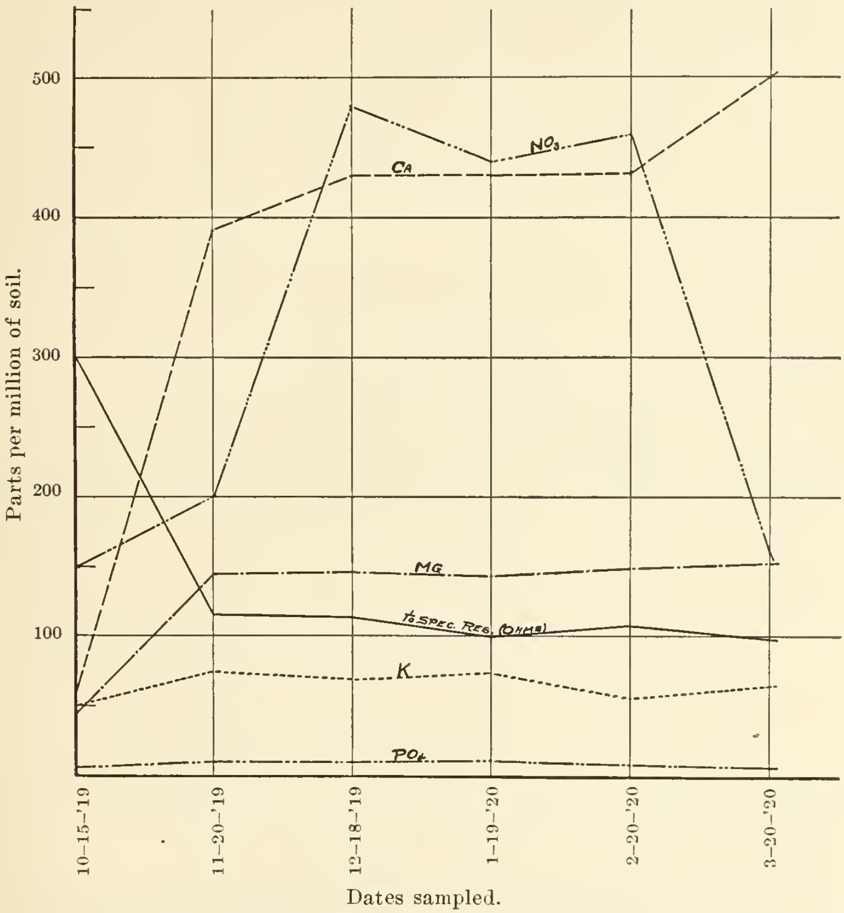

Fig. 12.—Water-soluble materials dissolved from cropped pot soils receiving both superphosphate and calcium carbonate.

are slightly different from those considered above. The calcium carbonate and the superphosphate treatments alone produced significant increases, while treatments of sodium nitrate and of potassium sulfate apparently decreased the yields, although the decreases are hardly significant. One can see from the data presented that liming to neutrality is the treatment *par excellence* for this soil type where

optimum moisture and temperature conditions obtain. The use of superphosphate without lime increases the yield of peas but 6%, while the addition of lime alone gives us an 18% increase over the check pots. In treatment 8, where both lime and superphosphate are applied, the yield is the same as where lime alone is used. The soil solubility studies to follow explain this point by showing that the calcium carbonate application renders soluble such amounts of soil

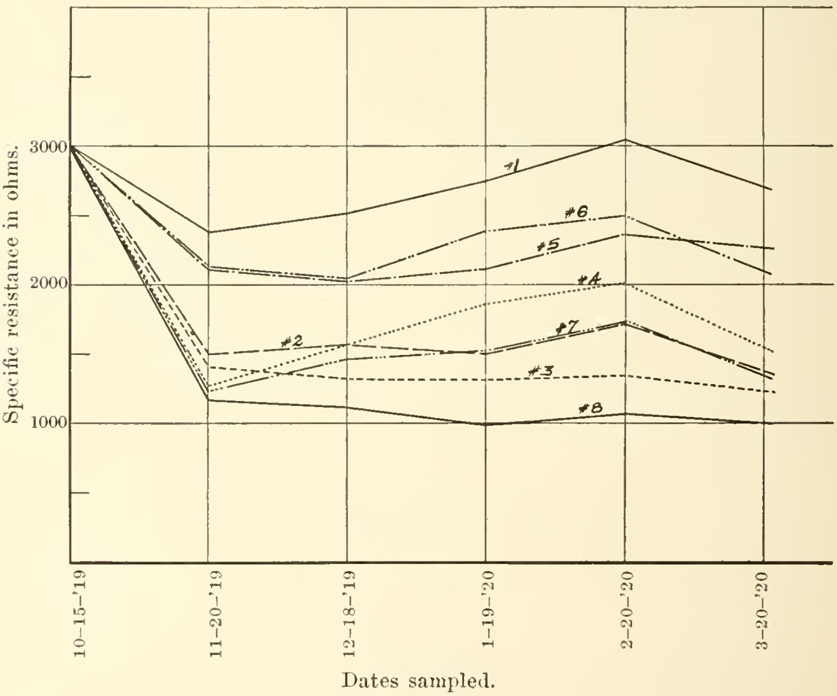

Fig. 13.—Effects of different treatments on specific resistances of water extracts.

phosphorus that still further applications of this element are unnecessary (see fig. 18, curves 4 and 8). At no time during the development of the plants in the greenhouse was the presence of soil toxins in any way manifested. Certain other points of interest regarding comparative yields will be noted later in connection with the soil solubility studies.

Immediately after harvesting (on April 10), the soils were carefully removed from the pots and the roots examined for nodule production. Previous experience in the field had shown this soil to be well supplied with the strain of *B. radicicola* capable of producing

nodules on pea roots. There was but little variation between the individual pots of the same treatment, the following general statements applying in each case:

Treatment No. 1: A few large nodules. Several small ones per pot.

Treatment No. 2: Similar to No. 1. Possibly a few more small nodules.

Treatment No. 3: A *very few* small nodules. But slightly better than No. 5.

Treatment No. 4: Best of all treatments. Large numbers of nodules both large and small. Many near bottom of pots.

Treatment No. 5: No nodules found.

Treatment No. 6: Very large numbers of small nodules. No large clusters.

Treatment No. 7: Large numbers of nodules, chiefly small, although a few large clusters were noted. Almost as good as No. 4.

Treatment No. 8: Very few small nodules. Similar to No. 3.

At first thought it might seem incredible that such an acid soil (P_H 4.5) could harbor viable strains of *B. radicicola*. Fred and Davenport,[12] however, in a series of very carefully controlled experiments, have given data to show that certain of the *B. radicicola* group are very resistant to acidity. All of the species apparently may withstand a reaction, in liquid media, of P_H 5. They state:

> The nodule bacteria from different plants behave very differently toward acid. The legume bacteria may be divided into groups about as follows:
>
> 1. Critical P_H—4.9 Alfalfa and sweet clover.
> 2. Critical P_H—4.7 Peas and vetch.
> 3. Critical P_H—4.2 Clover and common beans.
> 4. Critical P_H—3.3 Soy and velvet beans.
> 5. Critical P_H—3.15 Lupines.
>
> The evidence supports the conclusions that a correlation exists between the acid resistance of the bacteria and the acid resistance of the higher plant.

Since their bacteriological work was carried on in solution cultures, it may not be directly comparable with soil conditions, although it should be added that beans on the soil under experiment grow better than do either peas or alfalfa. This sequence would be expected from the data above presented.

Upon further observance of the effect of the soil treatments on nodule formation, we note that where nitrates were added, no nodules appeared, and, contrary to expectation, where $CaCO_3$ was applied to neutrality but *very few* small nodules were found. The reason is probably the same in both cases (see fig. 19, curves 3, 5, and 8),

namely, a superabundance of nitrate-nitrogen. Many articles are extant showing the depressing tendency of large amounts of soil nitrates on nodule formation. Superphosphate has often been observed to enhance nodule production. Our studies are in agreement with these findings. Potash and gypsum treatments but slightly enhanced nodule formation.

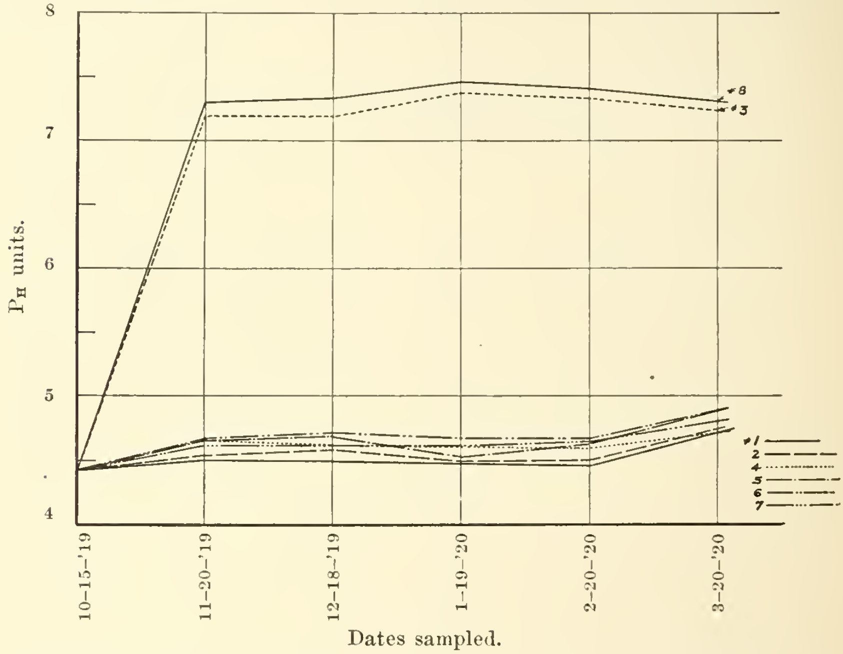

Fig. 14.—Effects of different treatments on hydrogen-ion concentrations of soils.

Soil Extraction Studies

It remains for us to discuss the interesting data secured by periodically extracting the differently treated soils with distilled water and noting the effects of both the fertilizer applications and the growing plants upon the concentration of soil solutes. The importance of knowledge of both the direct and the indirect effects of fertilizer chemicals upon soils has been briefly pointed out in the introduction to these studies. Stewart[44] has shown very fully the effects of a growing, unfertilized crop of barley upon the concentration of the soil solution. During the first six to eight weeks, a considerable increase in soluble nutrients was usually observed. This was especially true of nitrates. The growing crop then began to draw heavily upon this store with the

result that in most soils a gradual decrease in concentration was noted. He found that fertile soils were sometimes exceptions to this rule, the concentrations remaining practically constant throughout the entire growth period. The cause of this was pointed out as being doubtless due to the abilities of very fertile soils to renew soluble materials as

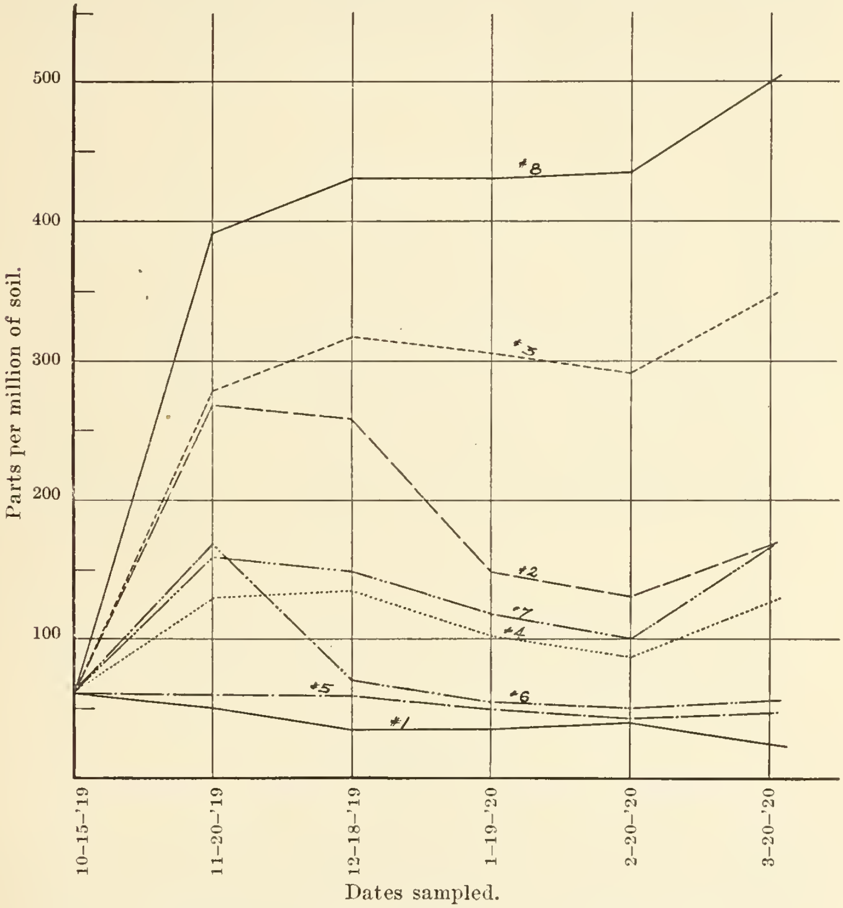

Fig. 15.—Effects of different treatments on calcium-ion solubility.

rapidly as they were withdrawn. Hoagland,[21] Millar,[34] and McCool and Millar[32] have shown that the solutes in the soil solution vary greatly at different periods and are materially affected by the growth of plants.

In the present investigation such effects are well shown in the curves presented in fig. 5. Upon the abscissae have been plotted the dates of sampling, while upon the ordinates appear the concentrations

of the various ions in parts per million of dry soil. Table VIII lists the data from which these curves were constructed. The graphs represent results secured from the eight check pots which received no fertilizing materials. Only slight differences in water-soluble potassium, magnesium, calcium, and phosphorus are here shown at the different sampling dates, while during the last two months a gradually declining tendency is noticed. The absolute amounts of these elements,

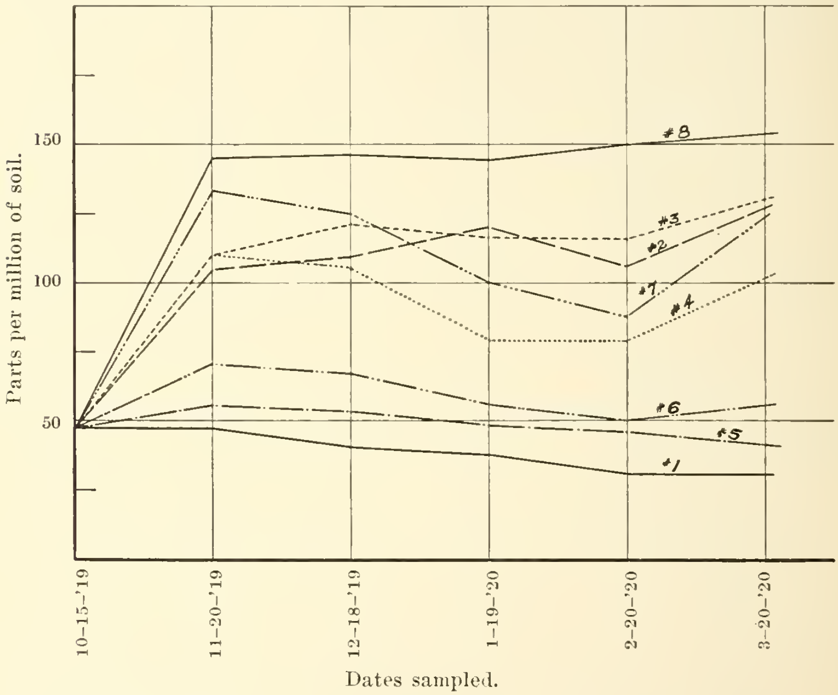

Fig. 16.—Effects of different treatments on magnesium-ion solubility.

present in a readily soluble form, are above those usually secured from the poor soils reported by Stewart, with the exception of PO_4-ion, the amount of which is unusually low. The nitrate-ion gradually increased in quantity during the first two months of growth, then fell off until, at the time of crop maturity, none remained. The results of the chemical work as carried out on the untreated field plot soils (fig. 3) are in close agreement with the greenhouse checks, except that nitrates, in the field, at no time equal the large quantities at first present in the irrigated pot soils.

Let us now briefly consider the effects of the several treatments upon the solubilities of the constituents of this clay loam soil. The

check pots, which received no additions, will be taken as the basis for comparison. Both the cropped and fallowed soils will be discussed.

The specific resistances of the soil extracts were always determined and are of importance in that they give us, in such dilute solutions, a comparative measure of total soluble salt concentrations. One-tenth of the specific resistance, in ohms, is shown by the solid lines in the graphs. It will be seen that these vary inversely with the concentra-

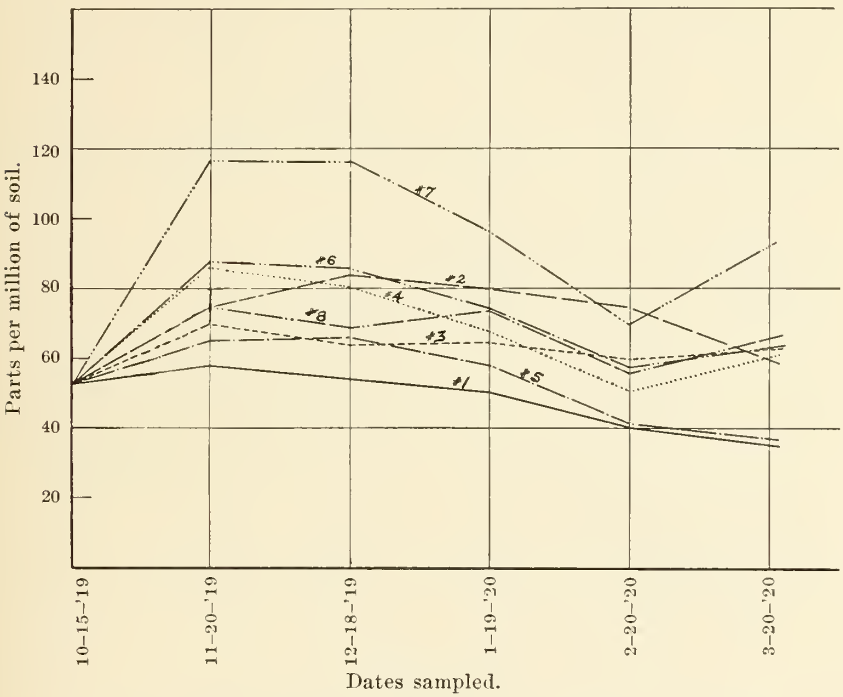

Fig. 17.—Effects of different treatments on potassium-ion solubility.

tion of soil solutes and that a general relationship exists between water-soluble salts and crop production.

Gypsum at the rate of one ton per acre was applied to the pots in treatment 2 (see fig. 6). Contrary to many general statements in the literature, nitrate production has not here been appreciably affected. The amount of water-soluble magnesium, however, has been increased almost threefold, while the amount of soluble potassium has been doubled under a rapidly growing crop. The amount of phosphate-ion was slightly increased at first, but soon fell to the level of the checks. Calcium, as would be expected, remained at a high level throughout the experiment. Sulfates, occasionally determined but not shown in

the graphs, were highest in the gypsum treatments. In the fallowed soils (Table IX), the results were much the same, except that the high level of concentration occurred a little later for all of the ions except magnesium. Here there was a gradual progressive increase. The actual concentrations of water-soluble compounds in the fallowed soils in all cases reached much higher levels than were reached in the cropped pots.

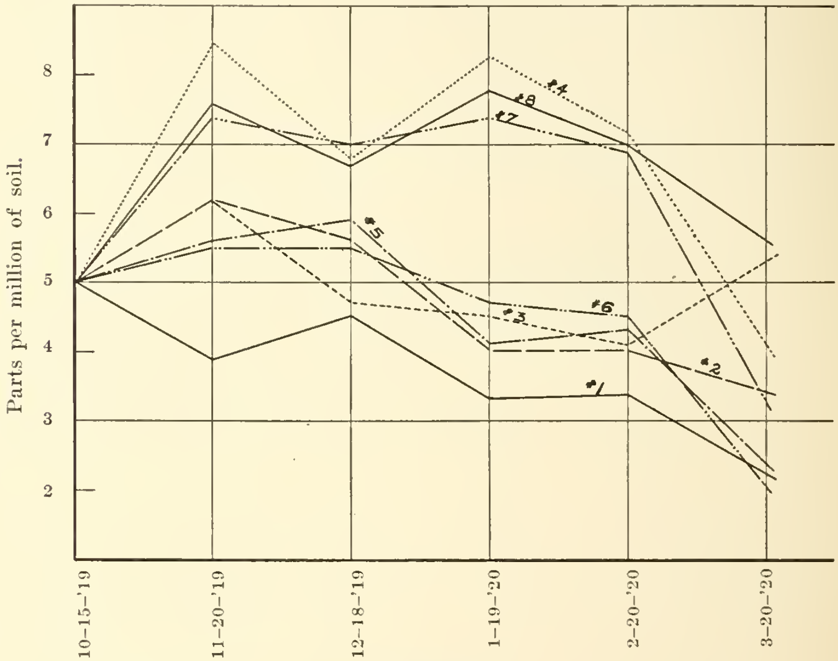

Fig. 18.—Effects of different treatments on phosphate-ion solubility.

The $CaCO_3$ applications increased nitrate production (from soil nitrogen) at least threefold throughout the growing period (see fig. 7). The same is true of the production of soluble magnesium. Soluble potassium and phosphorus are each increased by approximately 50 per cent. Calcium, in a readily water-soluble form, has been increased from an average of 40 p. p. m. in the checks to over 300 p. p. m. in the lime-treated pots. The specific resistance of the soil extract is very low throughout. With the exception of nitrate (and this tendency is also shown in the uncropped soil) the lime treatment not only *maintains* the concentrations of the several ions during the period of vigorous absorption of solutes, but actually increases the rate of solubility of

minerals over and above crop demands, for we see that, on March 20, at the time of maturity there is shown a slight rise in the phosphorus, potassium, magnesium, and calcium curves over the previous sampling date. It will be recalled that the $CaCO_3$ treated pots produced the maximum crops. In the fallowed soil (Table IX), the carbonate treatment produced by far the largest amount of soluble material, as shown by the specific resistances. In this case, also, the greatest con-

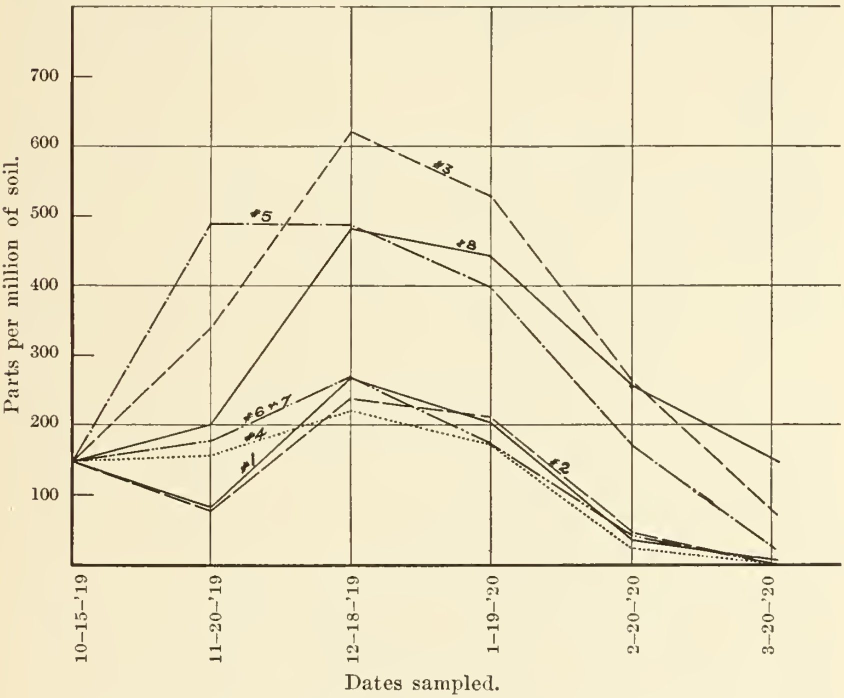

Fig. 19.—Effects of different treatments on nitrate-ion solubility.

centration of solutes appeared some weeks later than in the cropped soil. Magnesium was an exception. Here progressive solubility was gradual throughout. In both cropped and fallowed soils, gypsum and calcium carbonate were about equally effective in increasing magnesium solubility. A simple interchange of bases may possibly account for this. The solubility of the soil potassium is affected but slightly by the $CaCO_3$ additions.

Figure 8 shows the effect of superphosphate treatment. Figure 4, which records similar data for the field plots, may also here be of comparative interest. A notable similarity is shown between the two. A comparison of figure 8 with the check pots, figure 5, shows the addition

of superphosphate to have practically doubled the amounts of water-soluble phosphorus, calcium, and magnesium throughout the duration of the experiment, while nitrate formation, contrary to expectation, was slightly depressed by it. The same holds true, in the case of nitrates, for the fallowed soils, although nitrification in both cases increased at first more rapidly in the presence of the soluble phosphorus. In this series the cropped and uncropped soils behaved very similarly as regards progressive solubility; the soil, when receiving an application of acid phosphate, apparently being able to maintain the important solutes at fairly high concentrations during crop withdrawals.

The results for the $NaNO_3$ treatment are shown in figure 9. With the exception of the large amount of added nitrate, there is little difference between these soils and the checks. Thus, the nitrate application has had very little effect in increasing the solubility of this soil's constituents. This is in accordance with the recent work of Bauer,[3] who found that the presence of $NaNO_3$ had no effect upon the availability of soil phosphorus, and of Jensen,[23] who concluded that nitrate applications had no effect upon potassium availability and actually decreased a soils soluble phosphate content. Spurway,[43] on the other hand, shows additions of $NaNO_3$ to considerably increase the solubility of phosphorus and magnesium in the sandy soils which he investigated. The increases, however, are irregular, and the conditions imposed are most artificial. The fallowed soils receiving $NaNO_3$ gave increases over the checks, although the increments were small in comparison with those noted for other treatments. The crop results further showed that nitrate applications were unwarranted. The specific resistances were here at first slightly lower than were those of the checks, due to the soluble nitrate application, but even this difference disappeared as the end of the growing period was reached.

The potassium sulfate application, although slightly increasing water-extractable soil materials, also had no enhancing effect upon yields. It was applied at the rate of 500 pounds per acre. Figure 10 shows that water-soluble lime and potash have each been slightly increased during the period of active growth. The solubility of the phosphorus has been unaffected, as has nitrate production. Magnesium has been increased. The results secured with potassium sulfate in the fallowed soil are in fair agreement with these. The general relationships hold, although slightly larger quantities of solutes appear in all cases. A slow progressive solubility is recorded for each

ion determined except calcium, which apparently assumes its maximum concentration about a month or six weeks after the addition of the potassium sulfate and thereafter gradually declines. None of the solubility increases is marked.

In treatment 7, superphosphate (one ton per acre), together with potassium sulfate (500 pounds per acre), was added. The effects upon the solubility of the various ions determined are shown in figure 11. As would be expected, the soluble salt content has been considerably increased. Nitrates, however, remain approximately as in the check pots. No uncropped soils carrying two-salt treatments were maintained. The yields here were a surprise—much below those where superphosphate alone had been used. This may be due to "alkali," for analysis showed that Na_2SO_4 was present slightly in excess of 0.2 per cent. Improper balance of salts may also be advanced as a possible explanation for the lowered yields, as sulfate, calcium, magnesium, and potassium-ions are present in large quantities, while nitrates are present in relatively low amounts.

In the last series, applications of superphosphate and $CaCO_3$ were the treatments employed. The concentrations of the soil extracts were decidedly increased (see fig. 12), as shown by the conductivity measurements. The Ca-, NO_3-, and PO_4-ions especially showed greatly increased solubility. No tendency toward a decline in concentration during the period of rapid growth was evident. That soluble phosphate applications are superfluous when this soil is neutralized with lime is shown in figure 7. The ability of $CaCO_3$ to set free soluble phosphorus from soil minerals has also been recorded by Fraps,[11] Hartwell and Kellogg,[16] Guthrie and Cohen,[14] and others.

In order to compare more easily the effects of the individual treatments upon the solubility of each ion, a second series of curves was prepared. The complete hydrogen-ion and conductivity data are also presented. Let us glance at figure 13, which shows the effects of each treatment (1 to 8) upon the periodically determined specific resistances. The determination of specific resistance upon soil extracts is at the present time meeting with considerable favor among soil investigators. In alkali studies, where large numbers of soils must be examined for total soluble salts, its use is certainly to be recommended. That considerable precision may be claimed for it has been shown by von Horoath,[22] who has proposed a soil classification based upon electrical conductivity. In figure 13, the high concentrations of treatments 8 and 3 (where $CaCO_3$ was added) over the entire growth period are

well shown, while the low concentrations of the checks (1), the K_2SO_4 pots (6), and the nitrate treated soils (5), are likewise emphasized. Numbers, 2, 4, and 7 occupy intermediate positions. That the yields may be closely correlated with soluble salt concentrations (conductivities) has been previously noted. A comparison with figure 20 emphasizes this fact.

Considerable interest attends the data presented in figure 14. Hydrogen-ion determinations were made periodically upon these pot soils throughout the experiment, much care being taken to secure accurate, comparative results. It was desired to ascertain whether or not, during the growth of the crop, any of the fertilizer treatments, except, of course, $CaCO_3$, had in any way altered soil reaction, and also whether or not, after adding $CaCO_3$ to neutrality, any acidity subsequently developed. The abscissa shows the dates of sampling, while the ordinate is divided into the customary P_H units. The small, ten-gram samples used in making these determinations were carefully taken from the large monthly composite samples and were representative. The determinations were made upon the moist soils as soon as received from the greenhouse. A study of figure 14 shows that in treatments 3 and 8, sufficient $CaCO_3$ had been added to maintain an alkaline reaction (above P_H7), although the tendency to gradually decrease in alkalinity is shown at the last two sampling dates. While exactly the same amounts of $CaCO_3$ were supplied in both cases, it will be seen that the addition of superphosphate in treatment 8 rendered this soil *more alkaline* at all times. The same tendency to induce alkalinity is shown where superphosphate is added alone (compare treatment 3 with treatment 1), the checks being the most acid soils of all. These results are in direct agreement with those of Conner,[8] who has shown that soils that had been treated with acid phosphate for twenty years were *less* acid than the untreated soils. Morse[38] has determined hydrogen-ion concentrations colorimetrically on certain plot soils. In agreement with other investigators, he claims that acid phosphate, even though used over a long period of years, produced no noticeable effect on soil reaction, while, where lime was occasionally used with it, at the rate of one ton per acre, the superphosphate apparently further enhanced alkalinity. Small, definite differences also existed between the checks and the soils receiving the neutral salt treatments. It will be seen that the K_2SO_4 application has decreased the hydrogen-ion concentration throughout by at least three-tenths of a P_H—an amount too great to be considered experi-

mental error. This basic tendency of the other salts, while less pronounced, is, however, uniform and definite.

A decided upward trend of all of the curves (except 3 and 8) is noticeable from February 20 to March 20. The decreases in hydrogen-ion concentration are here too marked to be ascribed to error. A possible explanation for this is as follows: At the end of the growing season, a small fraction only of the nitrate still remains in these very acid soils (see figure 19). The soil solution must be practically saturated with CO_2 due to rapid root growth and high organic matter content. When the large amounts of nitrate are absorbed and removed from solution, the bases formerly associated with this strongly acid radical may combine with the weak H_2CO_3 forming bicarbonates of the strong bases (K, Na, Ca). Subsequent hydrolysis tends slightly to increase OH-ion concentration.

Another point which the writer deems of importance in connection with the reaction studies recorded is that strong soil acidity, per se, is *not necessarily* harmful to growth, and that it has in the past been over-emphasized as a cause of low productivity, especially in the case of leguminous crops. A glance at figure 21, together with the high yields secured in *all* cases, checks included, suffices to show that, even where such a ''lime loving'' legume as the pea is grown, other conditions being optimum, good results may be expected in the presence of high soil acidity. So far as the writer is aware there is no definite evidence in the literature to show that soil acidity of *itself* is the direct cause of infertility. Recent work at the University of California might be cited to show that heavy yields are often secured in solution cultures where hydrogen-ion concentrations are abnormally high. It is thus questionable whether *complete* neutralization, especially where high lime applications are necessary, is ever justified. Many cases have been noted where the satisfaction of a small fraction of the so-called ''lime requirement'' has increased yields to the same extent as have larger lime treatments.

The comparative calcium-ion concentrations in the variously treated soils appear in figure 15. In treatment 8, receiving both $CaCO_3$ and superphosphate, we find the most soluble calcium. This is followed by $CaCO_3$, gypsum, superphosphate plus K_2SO_4, and superphosphate alone. The K_2SO_4 and the $NaNO_3$ treatments had little effect in setting free soil calcium.

The behavior of magnesium-ion is of interest in that it follows closely that of calcium-ion solubility. A comparison of figure 16 with

figure 15 shows that there are no exceptions to this statement. As magnesium was in no case applied to the soils* in soluble form, there must have been a direct exchange of bases between this ion and those supplied in the treatments.

The solubility of soil potassium has been fully discussed. A direct graphical comparison of the treatments is shown in figure 17. The check soils (number 1) are the lowest in available potassium throughout, while, aside from the direct K_2SO_4 treatments, gypsum is, in the soil under study, apparently superior to all others in setting free potash. The efficacy of the superphosphate additions is here doubtless due to this ingredient. Recent work of McCool and Millar[33] bears out this statement. Calcium carbonate is much less effective. Slight increases only result from the $NaNO_3$ applications.

The percentage of water-soluble phosphate is unusually low in this soil and none of the treatments, except those directly supplying phosphate-ion, greatly alters its availability save $CaCO_3$ which has a slightly enhancing tendency toward the end of the experimental period. The check soils are a little below the others in the amounts of soluble phosphorus they contain, as shown in figure 18, although the differences are slight. That low concentrations of PO_4-ion are the rule in water extracts of soils has often been recorded. Certain data recently secured by the writer have shown that the same holds for the true soil solution as obtained by a direct pressure method. One to three p. p. m. of soil solution are here usually found. Work in this connection has been reported elsewhere.†

The nitrate-ion concentrations as plotted in figure 19 are of interest in that they closely agree with nitrification studies (not here reported). Except number 5, where $NaNO_3$ was directly supplied, the $CaCO_3$ treatments *alone* gave noteworthy increases. In all cases, however, sufficient nitrification may have taken place within this acid soil to supply crop requirements, although it should be recalled that a leguminous crop was grown.

While the results of these solubility studies apply to this soil alone, we are probably safe in considering them generally applicable to transported, low-lying acid clays and clay loams, comparatively high in organic matter and rich in nitrogen.

* The superphosphate alone gave slight traces.

† See Soil Science, vol. 13.

SUMMARY

The work herein reported embraces an investigation of an acid, marsh soil, unproductive for peas, by the use of certain of the more modern procedures. Both field and greenhouse experiments were conducted, a variety of fertilizing materials were employed, and soil-water-extracts, periodically made, were studied to ascertain the rates of formation, as well as the absolute amounts, of soluble salts formed in the soil when influenced by the different factors involved. This work has been supplemented by hydrogen-ion determinations and conductivity measurements. A detailed discussion of the results secured has been given in the body of the text, although a critical study of the data presented offers several points of theoretical interest.

Doubtless, the most important point made, aside possibly from the effects of the various treatments upon yields, is the remarkable *indirect* fertilizing action of certain of the chemical compounds when applied to this cropped, clay-loam soil. That this has been brought about by a process of ionic substitution, element for element, within the hydrated silicate molecules, thereby greatly increasing mineral solubility, is a probable explanation. Why certain bases, as calcium for instance, should be more active than sodium or potassium or why the SO_4-ion should be more reactive than either NO_3-ion or PO_4-ion are questions offering a good field for hypothesis and experiment.

In comparing field and greenhouse yields we see that while $CaCO_3$ had no effect whatever in the field, in the pot experiment it gave the largest crop. With superphosphate the results were reversed. As this was an unusually dry year in the field, while in the greenhouse moisture conditions were maintained at optimum, an explanation may possibly lie in the comparative solubilities of these two compounds. The action of the $CaCO_3$, being in large part due to its indirect effect through enhanced nitrification, requires considerable quantities of water, while, on the other hand, if sufficient moisture is present to dissolve but a small portion of the superphosphate, enhanced yields should result in a soil deficient in available phosphorus. Another effect of the field application of acid phosphate was to increase permanently the solubilities of all of the soil constituents except PO_4-ion. Soluble phosphorus was directly supplied, yet at the end of two months no indications of such applications were apparent in the water

extracts. Similar conditions were observed in the greenhouse pot soils. It has been noted that small quantities (12 to 14 p. p. m.) of soluble aluminum were consistently found in this soil. A simple explanation of rapid phosphate reversion may thus be found in a direct union between superphosphate and soluble aluminum, with the formation of insoluble aluminum phosphate. In a soil rendered alkaline with lime, however, no such reaction could occur due to the precipitation of all soluble aluminum, either as the hydroxide or as

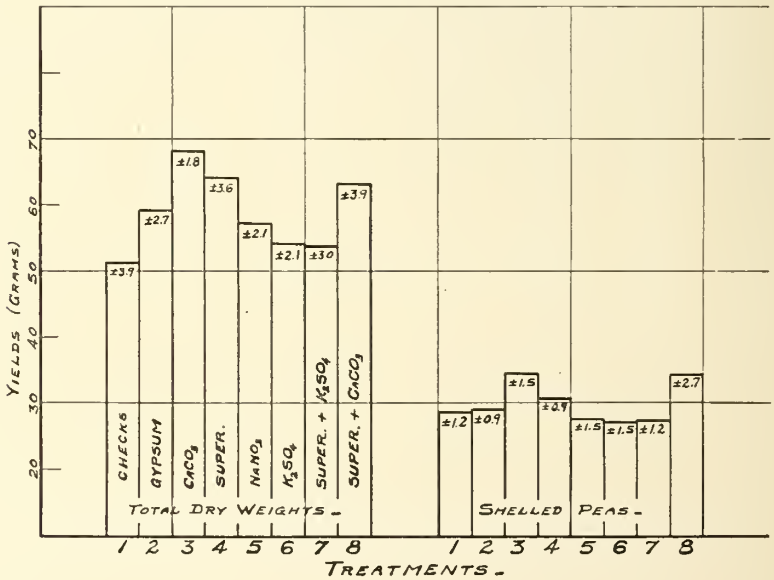

Fig. 20.—Comparative yields per pot of total dry matter and cured peas.

calcium aluminate,[36] as well as to the early formation of the reverted calcium phosphate which, so far as crops are concerned, is largely available. Such conditions do obtain in the $CaCO_3$-treated pots where maximum yields were registered and where moisture conditions were optimum. The curves here also show a slightly *enhanced* phosphate solubility which is maintained throughout the growing period.

A careful study of figures 5, 7, 11, and 12, together with comparative yields for these treatments (figure 20), casts some doubt as regards the power of soluble phosphorus to increase yields greatly in this soil unless soluble calcium also is present in adequate amounts. In figure 11 (superphosphate $+ K_2SO_4$) fairly large quantities of soluble PO_4-ion obtain (in fact, larger than appear in the $CaCO_3$-

treated pots), yet the yields are greatly in favor of the $CaCO_3$ additions. Large percentages of soluble calcium are shown at all times in figure 7. In figure 11, however, less than one-half of these amounts is present, while magnesium-ion concentration in this case is almost equal to that of calcium-ion. These results may show that a certain balance of ions within soil solutions is essential for optimum plant growth.

Fig. 21.—Plants one month before harvesting, showing the eight treatments.

Similar indications of the necessity for proper ionic ratios are shown in figures 7 and 9 where nitrates, phosphates, potassium, and calcium may be compared. The proportion of nitrates is high in both cases; the amounts of phosphates differ but 1 to 2 p. p. m., as is also the case with potassium, but calcium-ion is increased sixfold in the $CaCO_3$ treatment where the maximum yields are recorded. Other examples might be given which indicate that where anions are high, cations must also be present in certain definite optimum proportions.

A glance at the periodical conductivity measurements on the extracts from the variously treated soils shows that they arrange themselves exactly in the order of productivity. This method has been shown to be of great value in the study of alkali soils where large quantities of soluble salts prevail. May it not be of still greater value, in the absence of alkali, where estimates of comparative fertility are desired?

Soil acidity has been fully discussed in the light of data here presented and, except in the presence of unusually high hydrogen-ion concentrations (below P_H 4.5), it seems doubtful to the writer that acidity, per se, is ever the direct cause of low productivity provided sufficient concentrations of the basic ions (Ca, Mg, K) are present within the soil solution.

CONCLUSIONS

The following general conclusions may be drawn as the result of these investigations:

These studies were carried out on an acid, drained, heavy clay-loam, marsh soil of the San Francisco Bay region which was unproductive for certain crops and carried small percentages of the white alkali salts, notably sulfates.

Nitrification studies showed that the addition of calcium carbonate to neutrality greatly increased nitrate production, while soluble phosphorus and potassium compounds, without lime, produced no effect. Ammonification was largely due to soil fungi, and the *Azotobacter* species were absent.

A statistical study of the factor of variability, where certain water-soluble ions within soil extracts were taken as the criteria, showed that apparently uniform field soils may vary greatly within small areas; this is in accordance with the recent work of Waynick and Sharp.[48]

In the field, water was apparently the limiting factor in crop production at the Marin Meadows Ranch during the 1919–1920 season. Under those conditions superphosphate applied at the rate of one ton per acre increased yields by approximately 25 per cent while liming to neutrality gave no increases over the check plots. The chemical control maintained throughout the duration of the field experiment showed that the acid-phosphate applications had greatly enhanced the solubility of soil K, Mg, and Ca, while nitrate production was affected but slightly. The rapid revision of soluble phosphate within this soil was thought to be due largely to the formation of aluminum phosphate, for a small amount of aluminum-ion was always present in water extracts of this soil. Ferrous compounds or other toxic materials aside from the white alkali salts were not found.

In the greenhouse, where moisture and temperature conditions were optimum, much larger plants were produced. A 35% increase

(over the checks) in yield of total dry matter attended the use of $CaCO_3$, when added to neutrality, and a 28% increase where superphosphate at the rate of one ton per acre was applied. The soils receiving gypsum treatments and the checks were about equal in productivity, while $NaNO_3$, and K_2SO_4, each supplied at the rate of 500 pounds per acre, gave slight but insignificant losses. The yields of dried peas followed in a similar order.

Nodule formation as affected by these treatments within this very acid soil is discussed. Nitrates completely inhibited it, while $CaCO_3$ added to neutrality acted similarly (due doubtless to greatly enhanced nitrification). The application of soluble phosphorus increased nodule formation while potassium sulfate and gypsum produced no noticeable effects.

All of the chemical compounds added increased the concentration of the soil solutions under the growing crops when compared with the untreated checks, although marked differences between the several treatments were noted. A direct relationship existed between the concentration of solutes present in the soil extracts, as shown by conductivity measurements, and crop production. Gypsum was the most active liberator of the soil potassium and was equal to any other compound in effecting the solution of soil magnesium, while its action upon phosphorus availability and upon nitrate formation was nil. Calcium carbonate, when added to neutrality, was apparently the most effective soil solvent supplied, although its action was probably largely indirect. It occupies first place in effecting the solution of all ions, except potassium. In comparison with the checks, specific resistance was here decreased by almost one-half. This is doubtless due to the intensive nitrification which this treatment engenders. Nitrate production (from soil N) was nearly trebled, as was water soluble magnesium. Soluble calcium was increased many fold, and soluble K and PO_4 were each increased by at least one-third. With the possible exception of nitrate-ion concentration, which likewise fell off in the fallowed soil, there was no declining tendency noticed on the part of any of the nutritive ions during maximum withdrawals by the heavy pea crop produced.

The enhanced solubility of soil minerals due to superphosphate applications is probably largely to be attributed to the gypsum which this material contains. Bearing in mind that approximately twice as much calcium was supplied in the gypsum treatments, the similarity between the two is strikingly shown in figures 6 and 8. Soluble phoshorus, of course, was directly supplied in the superphosphate.

Sodium nitrate had little effect upon this soil's solubility in water throughout the duration of the experiments here reported.

Potassium sulfate applications increased the amounts of Ca and Mg going into solution by possibly one-third, while nitrate formation and phosphate availability were apparently unaffected.

The results secured from the two-salt applications, both as regards yields and soil solubilities, were approximately the same as the average of the similar individual single-salt treatments.

A periodical study of hydrogen-ion concentration was carried out on each of the differently treated pot soils throughout the cropping period. All of the soils to which neutral salts had been applied were slightly but consistently less acid than were the checks, superphosphate especially tending to lower H-ion concentration. During heavy nitrate absorption there was a slow, definite increase in soil alkalinity. On the other hand, where calcium carbonate had been added to neutrality, a progressive increase in H-ion concentration was recorded. The question is discussed as to whether soil acidity, per se, is ever a direct cause of impaired productivity.

The results, when cropped and fallowed soils were compared, differed but slightly, the chief dissimilarity being that the water extracts of the fallowed soils reached maximum concentrations about a month later than did those of the cropped soils, and thereafter remained stationary or gradually decreased. Larger amounts of solutes were, as a rule, present in the uncropped soils but the same comparative relationships almost invariably held. A series of fallowed soils is therefore held to be here superfluous, little additional information being gained, while the labor involved is approximately doubled.

In conclusion, the writer wishes to express his indebtedness to Professor C. B. Lipman, under whose direction this work was done. Thanks for many helpful suggestions and criticisms are also due Professor D. R. Hoagland and Professor W. P. Kelley.

LITERATURE CITED

[1] American Public Health Association. Laboratory Section.
1912. Standard methods for the examination of water and sewage. Ed. 2, 144 pp., bibl., pp. 137–140.

[2] Ames, J. W., and Schollenberger, C. J.
1916. Accumulation of salts in Ohio soils. Soil Sci., vol. 1, pp. 575–578.

[3] Bauer, F. C.
1920. The effect of leaching on the availability of rock phosphate to corn. Soil Sci., vol. 9, pp. 235–247.

[4] Blair, A. W., and Prince, A. L.
1920. The lime requirement of soils according to the Veitch method, compared with the hydrogen-ion concentration of the soil extract. Soil Sci., vol. 9, pp. 253–259, fig. .2.

[5] Burd, J. S.
1918. Water extractions of soils as criteria of their crop-producing power. Jour. Agr. Res., vol. 12, no. 6, pp. 297–309.

[6] Christie, A. W., and Martin, J. C.
1918. The chemical effects of CaO and $CaCO_3$ on the soil. Part II. The effect of water-soluble nutrients in soils. Soil Sci.. vol. 5, pp. 383–392.

[7] Coffee, G. N., and Tuttle, H. F.
1915. Pot tests with fertilizers compared with field trials. Jour. Am. Soc. Agron., vol. 7, pp. 129–139.

[8] Conner, S. D.
1916. Acid soils and the effect of acid phosphate and other fertilizers upon them. Jour. Indus. and Eng. Chem., vol. 8, pp. 35–40.

[9] Conner, S. D.
1917. Excess soluble salts in humid soils. Jour. Am. Soc. Agron., vol. 9, pp. 297–301.

[10] Davenport, C. B.
1904. Statistical methods. John Wiley and Sons, New York.

[11] Fraps, G. S.
1915. Effect of additions on availability of soil phosphates. Texas Agr. Expt. Sta. Bull. 178, 15 pp.

[12] Fred, E. B., and Davenport, A.
1918. Influence of reaction on nitrogen-assimilating bacteria. Jour. Agr. Res., vol. 14, pp. 317–336, fig. 1.

[13] Greaves, J. E., and Carter, E. G.
1919. The action of some common soil amendments. Soil Sci., vol. 7, no. 2, pp. 121–160, fig. 2.

[14] Guthrie, F. B., and Cohen, B.
1907. Note on the effect of lime upon the availability of the soil constituents. Jour. and Proc. Roy. Soc. N. S. W., vol. 41, pp. 61–66.

[15] Hager, G.
1918. The injurious actions of potassium and sodium salts on the structure of soils and their causes. Jour. Landw., vol. 66, pp. 241–286.

[16] Hartwell, B. L., and Kellogg, J. W.
1905. The phosphoric acid removed by crops, by dilute nitric acid and by ammonium hydroxide from a limed and an unlimed soil. 18th Ann. Rpt. R. I. Agr. Expt. Sta., pp. 253–255.

[17] Hartwell, B. L., and Pember, F. R.
1918. Aluminum as a factor influencing the effect of acid soils on different crops. Jour. Am. Soc. Agron., vol. 10, pp. 45–47.

[18] Hartwell, B. L., and Pember, F. R.
1918. The presence of aluminum as a reason for the difference in the effect of so-called acid soil on barley and rye. Soil Sci., vol. 6, pp. 259–277, plate 1.

[19] Hibbard, P. L.
1919. The alkalimetric determination of small amounts of magnesium. Jour. Indus. and Eng. Chem., vol. 11, pp. 753–757.

[20] Hibbard, P. L.
1919. The volumetric determination of sulfates by oxidation of benzidine sulfate with $KMnO_4$. Soil Sci., vol. 8, pp. 61–65.

[21] Hoagland, D. R.
1918. The freezing point method as an index of variations in the soil solution due to season and crop growth. Jour. Agr. Res., vol. 12, pp. 369–395, fig. 9.

[22] Horoath, Bela von
1916. The classification of soils according to their electric conductivity. Intern. Mitt. Bodenk., vol. 6, p. 231. Abstract in Chem. Abs., vol. 13, p. 488.

[23] Jensen, C. A.
1916. Solubility of plant-food elements as modified by fertilizers. Jour. Am. Chem. Soc., vol. 8, no. 2, pp. 100–105.

[24] Joffe, J. S.
1920. Hydrogen-ion concentration measurements of soils in connection with their ''lime-requirements.'' Soil Sci., vol. 9, pp. 261–266, fig. 2.

[25] King, F. H.
1906. Investigations in soil management, being three of six papers on the influence of soil management upon the water-soluble salts in soils and the yield of crops. 168 pp., 21 figs. Madison, Wis. (Pub. by author.)

[26] King, F. H.
1904. Investigations in soil management. U. S. D. A. Bur. Soils, Bull. 26, 205 pp., 9 figs., 4 plates.

[27] Knight, H. G.
1920. Acidity and acidimetry of soils. III. Comparison of methods for determining lime requirements of soils with hydrogen electrode. IV. Proposed method for determination of lime requirement of soils. Jour. Indus. and Eng. Chem., vol. 12, pp. 559–562.

[28] Lipman, C. B.
1918. A revolution in the theories and methods of soil chemistry. Proceedings of Thirty-eighth Annual Meeting of Society for Promotion of Agricultural Science, pp. 33–40.

[29] LIPMAN, C. B., and GERICKE, W. F.
1918. Does $CaCO_3$ or $CaSO_4$ treatment affect the solubility of the soil's constituents? Univ. Calif. Publ. in Agri. Sci., vol. 3, no. 10, pp. 271–282.

[30] LYON, T. L.
1911. Some experiments to estimate errors in field plot tests. Proc. Am. Soc. Agron., vol. 3, pp. 89–114.

[31] MACINTIRE, W. H.
1919. The liberation of native soil potassium induced by different calcic and magnesic materials, as measured by lysimeter leachings. Soil Sci., vol. 8, pp. 337–394, plate 1.

[32] MCCOOL, M. M., and MILLAR, C. E.
1918. Soluble salt content of soils and some factors affecting it. Mich. Agr. Expt. Sta. Tech. Bull. 43.

[33] MCCOOL, M. M., and MILLAR, C. E.
1920. The effect of calcium sulfate on the solubility of soils. Jour. Agr. Research, vol. 19, no. 2, pp. 47–54.

[34] MILLAR, C. E.
1919. The comparative rate of formation of soluble material in cropped and virgin soils as measured by the freezing point method. Soil Sci., vol. 7, pp. 253–257.

[35] MIYAKE, K.
1916. The toxic action of soluble aluminum salts upon the growth of the rice plant. Jour. Biol. Chem., vol. 25, pp. 23–28.

[36] MIRASOL, J. J.
1920. Aluminum as a factor in soil acidity. Soil Sci., vol. 10, pp. 153–217, plates 1–12.

[37] MORGAN, J. O.
1911. The effect of soil moisture and temperature on the availability of plant nutrients in the soil. Proc. Am. Soc. Agron., vol. 3, pp. 191–249. (See pp. 210–212.)

[38] MORSE, F. W.
1918. Effect of fertilizers on hydrogen-ion concentration in soils. Jour. Indus. and Eng. Chem., vol. 10, pp. 125–126.

[39] OSTWALD and LUTHER
1910. Hand- und Hülfsbuch zur Ausführung Physiko-Chemischer Messungen (dritte Auflage). See pp. 461–477.

[40] RUSSELL, E. J.
1917. Soil conditions and plant growth. Ed. 3, Longmans, Green and Co., London and New York.

[41] SHARP, L. T.
1916. Fundamental inter-relationships between soluble salts and soil colloids. Univ. Calif. Publ. in Agr. Sci., vol. 1, pp. 291–339, 3 figs.

[42] SHARP, L. T., and HOAGLAND, D. R.
1916. Acidity and absorption in soils as measured by the hydrogen electrode. Jour. Agr. Res. vol. 7, no. 3, pp. 123–145, 1 fig.

[43] SPURWAY, C. H.
1919. The effect of fertilizer salts treatments on the composition of soil extracts. Mich. Agr. Expt. Sta. Tech. Bull. 45.

[44] STEWART, G. R.
1918. Effect of season and crop growth in modifying the soil extract. Jour. Agr. Res., vol. 12, no. 6, pp. 311–368.

[45] TRUOG, E., and SYKORA, J.
1917. Soil constituents which inhibit the action of plant toxins. Soil Sci., vol. 3, pp. 333–351, plate 5. Lit. cit., pp. 349–351.

[46] WATT, R. D.
1909. An interesting soil problem. Transvaal Agr. Jour., vol. 7, pp. 428–429.

[47] WAYNICK, D. D.
1918. Variability in soils and its significance to past and future soil investigations. I. A statistical study of nitrification in soils. Univ. of Calif. Publ. in Agr. Sci., vol. 3, no. 9, pp. 243–270.

[48] WAYNICK, D. D., and SHARP, L. T.
1919. Variability in soils and its significance to past and future soils investigations. II. Variations in nitrogen and carbon in field soils and their relation to the accuracy of field trials. Univ. of Calif. Publ. in Agr. Sci., vol. 4, no. 5, pp. 121–139.

[49] WHEELER, H. J., BROWN, B. E., and HOGENSON, J. C.
1903. A comparison of results obtained by the method of cultures in paraffined wire pots with field results on the same soil. R. I. Agr. Expt. Sta., Bull. 109, 16 pp.

[50] WOOD, T. B., and STRATTON, F. J. M.
1910. The interpretation of experimental results. Jour. Agr. Sci. (London), vol. 3, pp. 417–440, figs. 10.

[51] WOOD, T. B.
1911. The interpretation of experimental results. Jour. Bd. Agr. (London), vol. 18 (Supp. no. 7), pp. 15–37, fig. 2.